Background Information for Use of Pitot Tube, Manometer, Hot Wires, and Hot Films

1 Background

The following is adapted from the handout in AAE333L.

1.1.1 Specific Applications:

Hot wires are the most common instrument for measuring unsteady fluid flows. Most real fluid flows are turbulent and unsteady. Pitot tubes are the simplest standard flow-measurement technique.

DO NOT FORCE THE HOT FILM OR PITOT TUBE INTO THE WALL OR STOPS!
BE GENTLE WITH THE TRANSLATION STAGE!

1.1.2 The Pitot-Static Tube

For inviscid incompressible (i.e., ignoring the effects of viscosity and assuming density is constant) flow the principle of continuity and the Bernoulli equation become useful in determining average flow properties along a streamline. Time-average velocity measurements can be made with a pitot-static tube.

The operation of a pitot-static tube is based upon the Bernoulli equation which for a steady incompressible flow takes the form:

$$P_s + \frac{1}{2}\rho U^2 = P_t$$

where:

U = average flow velocity

ρ = fluid density (assumed constant in Bernoulli equation)

P_s = static pressure

P_t = total pressure

$\frac{1}{2}\rho U^2$ = dynamic pressure (by definition)

The pitot-static tube is a combination of a pitot or total head tube for measuring total pressure and a static tube for measuring static pressure in the flow, thereby allowing the velocity to be determined at the point of measurement (see Figure 1).

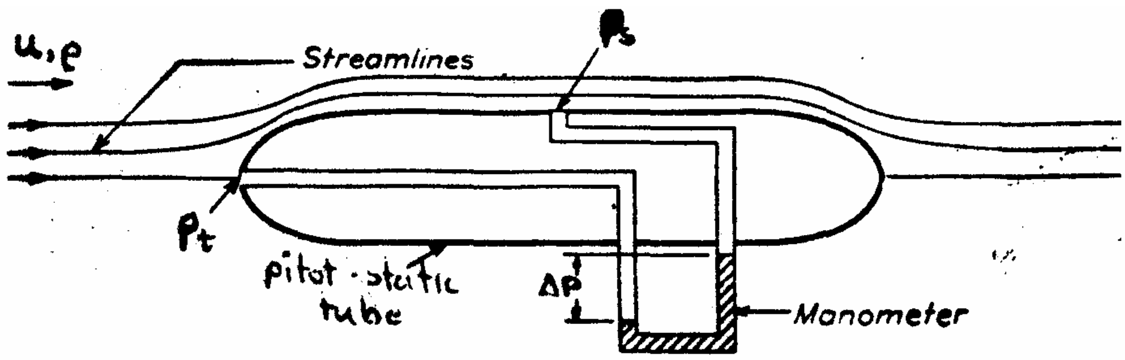

Figure 1

The flow entering the pitot-static tube at the open end is brought to rest (U=0) at the stagnation point. This tube provides the total pressure. The static pressure must be measured perpendicular to the flow, thus ignoring the effects of velocity. This is accomplished by using carefully positioned holes in the side of the pitot-static tube.

A differential manometer can read directly the dynamic pressure $q = 1/2\ \rho U^2 = \Delta P$. Therefore the velocity of the fluid is ($\Delta p = P_t - P_s$):

$$\mathbf{U} = \sqrt{\frac{2(P_t - P_s)}{\rho}}$$

1.1.3 Hot Wire and Hot Film Sensors

The principle on which the operation of a hot wire or a hot film sensor is based is very simple and can be explained as follows: If a piece of electrically heated fine wire is placed normal or at some angle to a flow stream, the wire will be cooled by the flowing fluid due to the heat transferred from the wire to the fluid provided the sensor is at a temperature above the fluid temperature. The amount of heat transferred is related to the magnitude of the velocity and should increase with increasing velocity. THE PHYSICAL QUANTITY WHICH IS MEASURED BY THE HOT FILM ANEMOMETER IS THE HEAT TRANSFER RATE FROM THE WIRE TO THE FLUID.

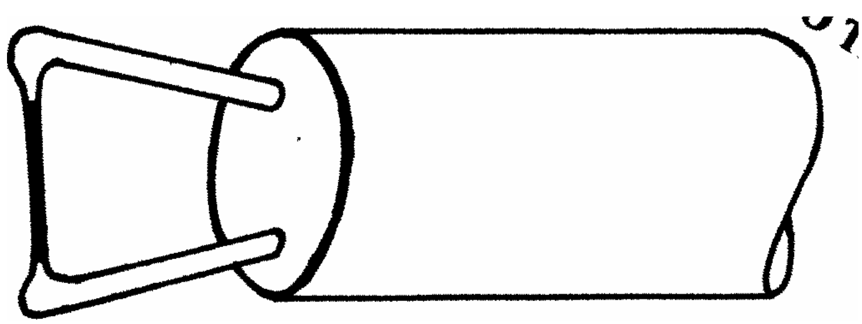

Figure 2 Sensor

1.1.4 The Sensor

Two kinds of sensors have been developed and they are presently in use, the hot wire and the hot film. Both are attached to fine needles that point forward into the flow (Fig. 2). Both are usually placed perpendicular to the primary flow direction. The hot wire is typically made of tungsten or platinum-rhodium, and is a fine wire that is typically 0.00005 to 0.0002 inches in diameter and 0.010 to 0.040 inches long. The hot film comes in various forms. The ones commonly used consist of fine quartz filaments, typically 0.001 to 0.006 inches in diameter, and 0.010 to 0.080 inches long. The quartz filament is covered with a thin *film* of vacuum-deposited metal, usually platinum. The film is more robust, due to the larger-diameter substrate, but tends to have a lower frequency response. The unsteady response of the films is very difficult to calibrate accurately due to the problem of unsteady heat transfer into the quartz substrate.

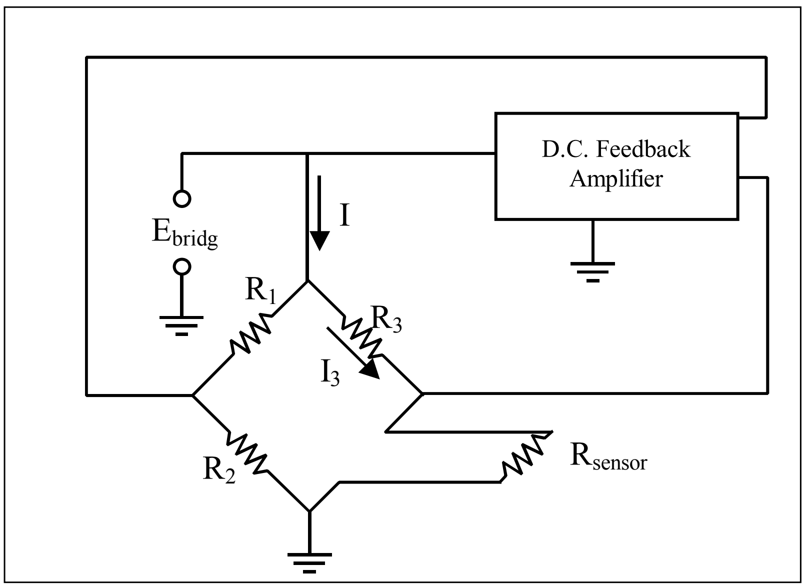

Figure 3. Constant Temperature Mode Schematic

The advantages in using hot-film or hot-wire anemometry are (1) the small size of the sensor, which permits minimal disturbance of the flow characteristics, (2) the high frequency response, permitting turbulence measurements, and (3) the high sensitivity at very low velocities, in both gases and liquids. The disadvantages of hot-film anemometry are the high cost of the instrument, the complicated electronics and associated difficulties in measurement, and the fragile nature of the sensors.

Hot-film or hot-wire sensors will be used in constant-temperature mode to measure velocity. The electronic circuit of a constant-temperature anemometer is shown in Figure 3. The sensor is one of the resistors of the Wheatstone bridge. When the sensor starts to cool due to an increase in the flow velocity, its resistance begins to decrease. The infinitesimal reduction in the sensor resistance begins to unbalances the bridge, which is then balanced almost instantaneously by the feedback amplifier, through an increase in the current through the Wheatstone bridge. The added current results in an increase in temperature, and thus in sensor resistance. The feedback system thus keeps the temperature of the sensor constant.

1.1.5 The Physics Of Sensor Heat Transfer

We have already stated that the operation of the hot film anemometer is based on measuring the heat-transfer rate from the sensor to the fluid. This heat-transfer rate will depend on the velocity of the fluid, and the fluid density, viscosity, thermal conductivity, coefficient of thermal expansion, and specific heat. It also depends on the diameter and surface area of the wire and on the temperature difference between the wire and the fluid.

Dimensional analysis shows that these quantities can be reduced to four nondimensional numbers. That is, the heat transfer from the wire to the fluid is described by an equation of the form

$$Nu = f(Re, Gr, Pr)$$

where

Nu is Nusselt Number

Re is Reynolds Number

Gr is Grashof Number

Pr is Prandtl Number

Nu is the Nusselt number defined as:

$$Nu = \frac{\text{Total Heat Transfer}}{S k_f \frac{(t_s - t_f)}{d}}$$

where

S = surface area of sensor (hot film)
d = sensor diameter
k_f = thermal conductivity of the fluid at temperature $(t_s + t_f)/2$
t_s = sensor temperature
t_f = fluid temperature

Since $S\,k_f\,(t_s - t_f)/d$ is proportional to the amount of heat conducted away from the sensor, it follows that Nu is a measure of the importance of the convective heat transfer in comparison with the total heat transfer. Large Nu implies that most of the heat is taken away from the sensor through convection, and thus the conduction mechanism can be neglected.

Gr is Grashof number. Gr is associated with free convection, namely, convection due to buoyancy forces, and is a measure of this effect. Gr is most commonly interpreted as the nondimensional ratio of the buoyancy force times the inertia force divided by the viscous force squared. For measurements in air the buoyancy forces can usually be neglected, as long as the air is not completely still.

Pr is the Prandtl number defined as:

$$Pr = \frac{\rho C_p \nu}{k_f} = \frac{\nu}{\alpha}$$

where

ρ = fluid density
ν = kinematic viscosity of fluid = μ / ρ
k = thermal conductivity
C_p = specific heat of fluid under constant pressure
$\alpha = \frac{k_f}{\rho C_p}$ = fluid thermal diffusivity.

The Prandtl number is a property of the fluid. It compares the ability of the fluid to diffuse momentum to its ability to diffuse heat.

Finally, Re is the Reynolds number, $Re = U_\infty d / v$, which is a measure of the ratio of the inertia forces to the viscous forces.

For our measurements in air, Pr is constant and the influence of Gr can be neglected. Therefore, the heat transfer in this case is described by an equation of the form

$$Nu = f(Re) .$$

By definition we have:

$$Nu = \frac{Q}{\pi l d k_f \frac{(t_s - t_f)}{d}} = \frac{Q}{\pi l k_f (t_s - t_f)}$$

where Q is the heat per unit time transferred from the sensor to the fluid, and l is the length of sensor (hot film). However, since the anemometer maintains the sensor at a constant temperature, the electric power provided to the sensor, P, should be equal to Q, P = Q.

From the circuit we have:

$$P = (I_3)^2 R_H = \left(\frac{E}{R_3 + R_H}\right)^2 R_H$$

where E is the bridge voltage, R_H is the sensor operating resistance, and R_3 is the resistance of the bridge leg that is in series with sensor (since the current into the amplifier can be neglected). Thus,

$$Nu = \frac{1}{\pi l k_f \Delta T} \cdot \frac{R_H}{\left(R_H + R_3\right)^2} E^2 .$$

One additional reduction can be made in order to express the Nusselt number in terms of readily obtainable quantities. Since our sensor is a conductor we can write

$$R_H = R_c(1 + \alpha'\Delta T),$$

where R_c is the sensor "cold" or "environmental" resistance (to be measured), and α' is the temperature coefficient of resistance for the sensor. The ratio R_H/R_c is called the overheat ratio.

Using this relation, we finally arrive at:

$$Nu = \frac{\alpha'}{\pi l k_f} \frac{R_c R_H}{\left(R_H - R_c\right)\left(R_H + R_3\right)^2} E^2$$

and

$$Re = \frac{U_\infty d}{v}.$$

By measuring E as a function of U, one can plot Nu as a function of Re, as shown in Figure 4 on a log-log scale. The linear graph indicates Nu varies as Re raised to some power, plus a constant.

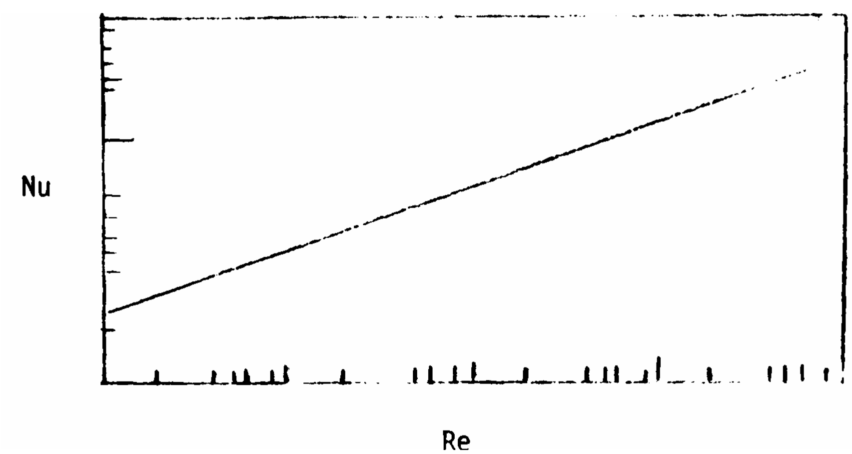

Figure 4: Nominal Hot-Wire Calibration

In practice one may calibrate the instrument by finding E as a function of U_∞. A calibration of this kind looks like the curve shown in Figure 5.

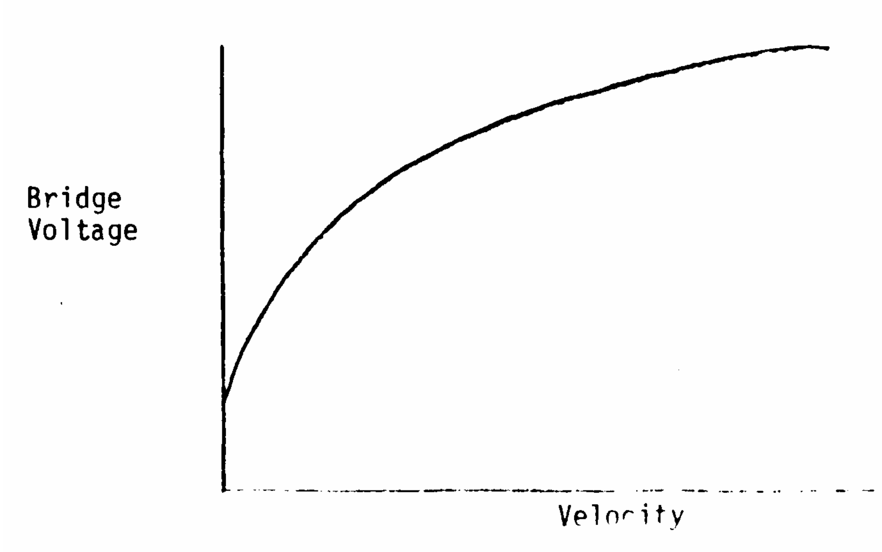

Figure 5: Typical Low-Speed Hot-Wire Calibration

At low speeds, the results can be fitted to a simple empirical formula, **King's Law,**

$$Nu = A + B\sqrt{Re} \ .$$

This yields a curve-fit of the form

$$E^2 = c_o + c_1\sqrt{U} \ .$$

The curve-fit fails at low velocities where buoyancy effects become important. Thus, zero-velocity data should not be used in the calibration!

1.1.6 Summary Of Hot Film Anemometer

The hot film anemometer is a very thin piece of wire. The wire can be heated to a desired temperature by placing a certain current through it. The current through the anemometer is determined by the bridge voltage (E). Using R_c and R_H we can set the wire temperature to any value desired. Once the anemometer is set to a certain temperature the electronics of the system are such that the anemometer is kept at this temperature. This constant temperature will remain as it is set.

As the air begins to flow over the wire it tries to cool the wire, thus trying to reduce the temperature of the wire. To keep the wire at the set temperature, the current through the wire increases. As the current increases, the bridge voltage (E) also increases, and this is what is measured. As the velocity of air over the wire increases it takes more bridge voltage (E) to maintain the wire at the set temperature. Thus there is a relationship between the velocity over the wire and the bridge voltage.

1.1.7 Typical Unsteady Signals from a Hot-Film or Hot-Wire Anemometer

This section shows some signals taken using the IFA-100 anemometer and the LeCroy 9304AM. A hot film is in operation at an overheat of about 1.25, in the AAE333L Basic Flow Measurements pipe apparatus.

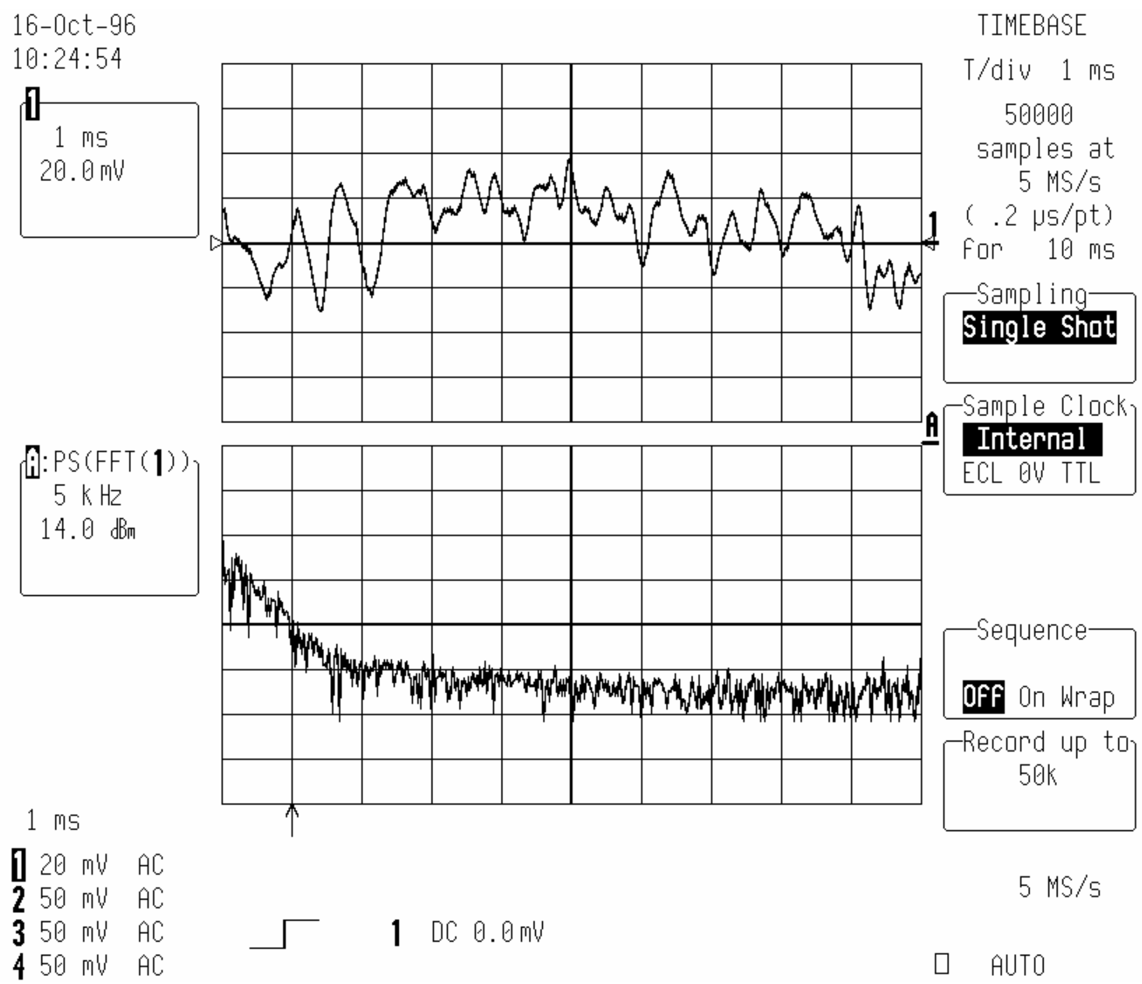

Figure 6: Typical Hot-Film Signal, with Blower Door 1/3 Open

In Fig. 6, the turbulent fluctuations are roughly 60mV peak-peak, and the power spectrum or FFT rolls off smoothly with increasing frequency. The power is all below 20kHz in typical low speed flows. Here, the power is all below 10kHz, the rest is electronic noise.

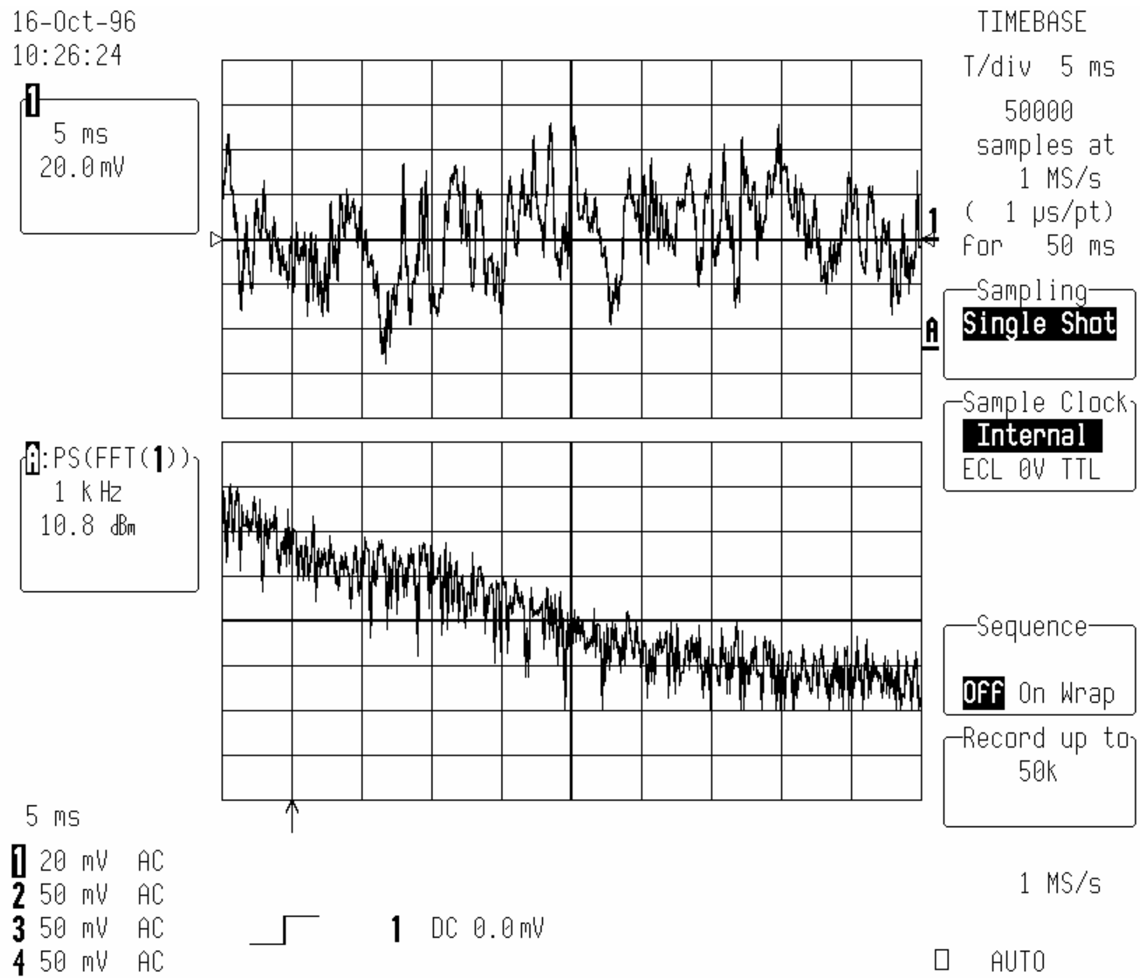

Figure 7: Typical Turbulent Hot-Film Signal, same conditions as Fig. 6, with Different Scope Settings

Figure 7 shows the signal content at lower frequencies.

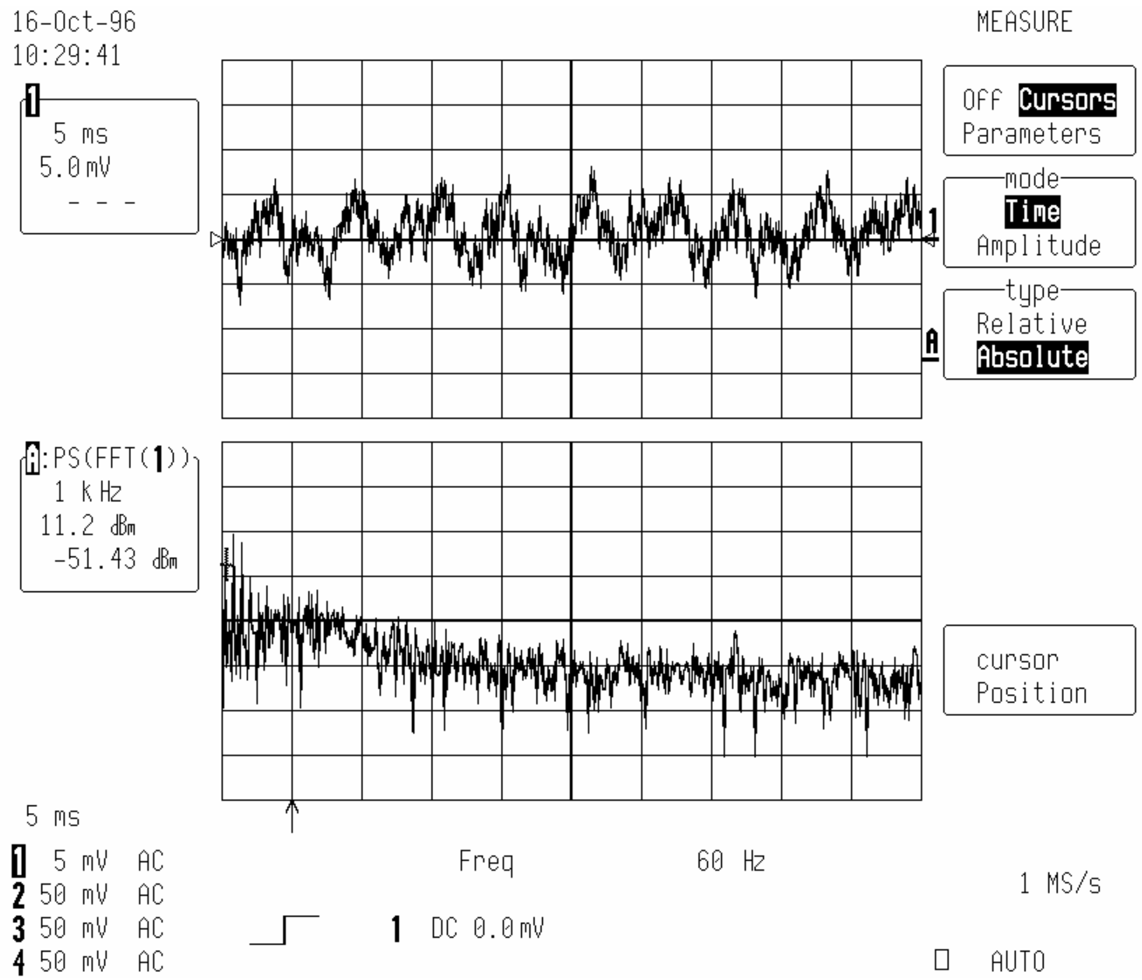

Figure 8 No-Flow Hot-Film Signal, Normal Operation

Fig. 8 shows a signal obtained in the AAE333L apparatus with the blower off. The noise is typically 5-10mV peak-peak. The FFT shows a number of spikes at 60Hz and multiples, such as 180Hz. These are caused by electromagnetic pickup from the blower motor and other AC devices. This is a normal no-flow signal.

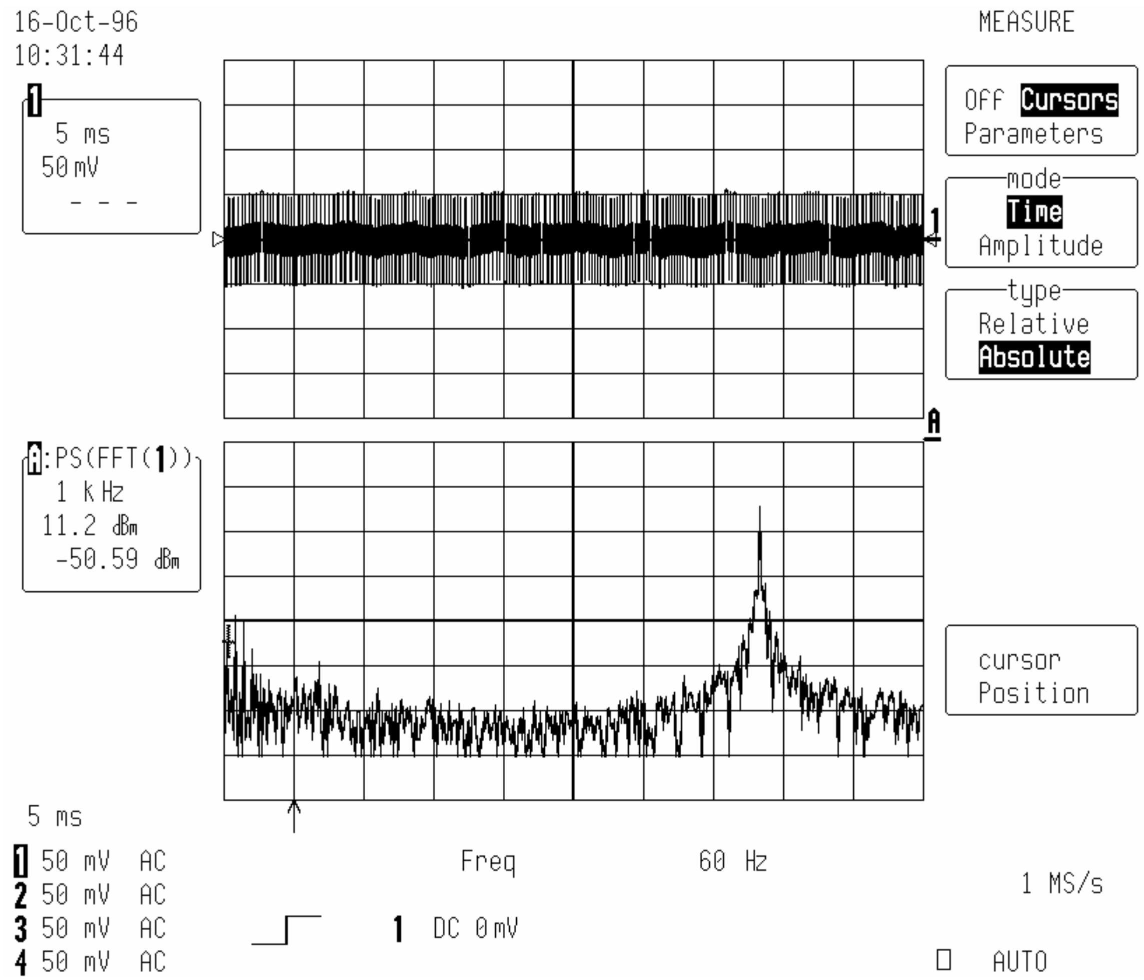

**Figure 9 Abnormal Signal from Hot-Film,
Shows Aliased Self-Oscillating Behavior**

Fig. 9 shows what can happen when the "Frequency Compensation" is wrong (cable compensation and bridge compensation knobs). The feedback system becomes unstable and oscillates. ALL OUTPUT UNDER THESE CONDITIONS IS USELESS, IT REFLECTS ONLY ELECTRONIC PROBLEMS. You must watch out for this problem while you are running the anemometer, it can develop over time as connections go bad, etc. NOTE ALSO THAT THIS PARTICULAR TRACE IS ALIASED! THE REAL POWER IS AT MHZ FREQUENCIES, WHICH CANNOT BE CAPTURED WHEN SAMPLING AT 1 MHZ.

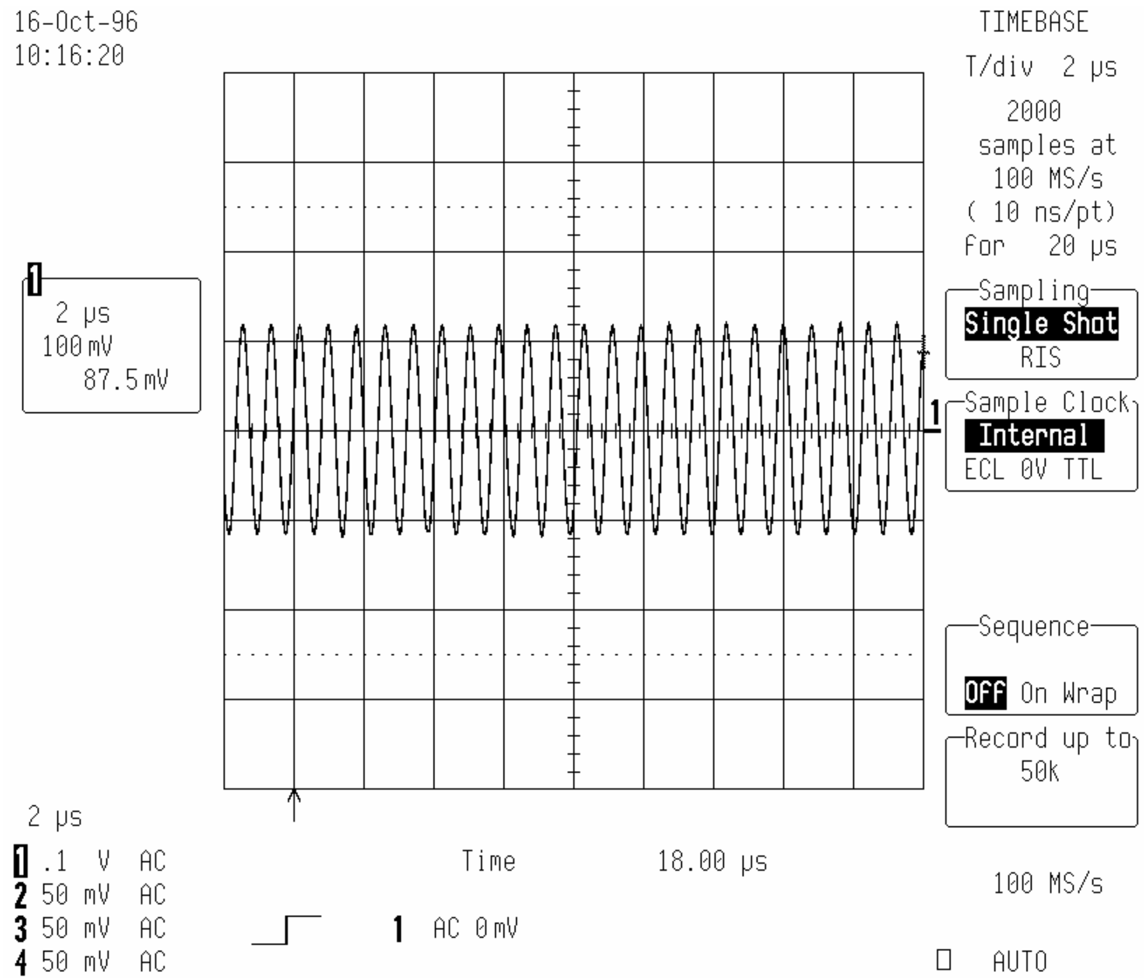

**Figure 10: Abnormal Signal from Hot Film,
Showing Unaliased Self-Oscillations**

Fig. 10 shows the same signal acquired at a higher sampling rate. You can see the hot-film system is oscillating at several megahertz. This high-frequency clean tone is a definitive sign of electronic oscillations in the feedback circuit.

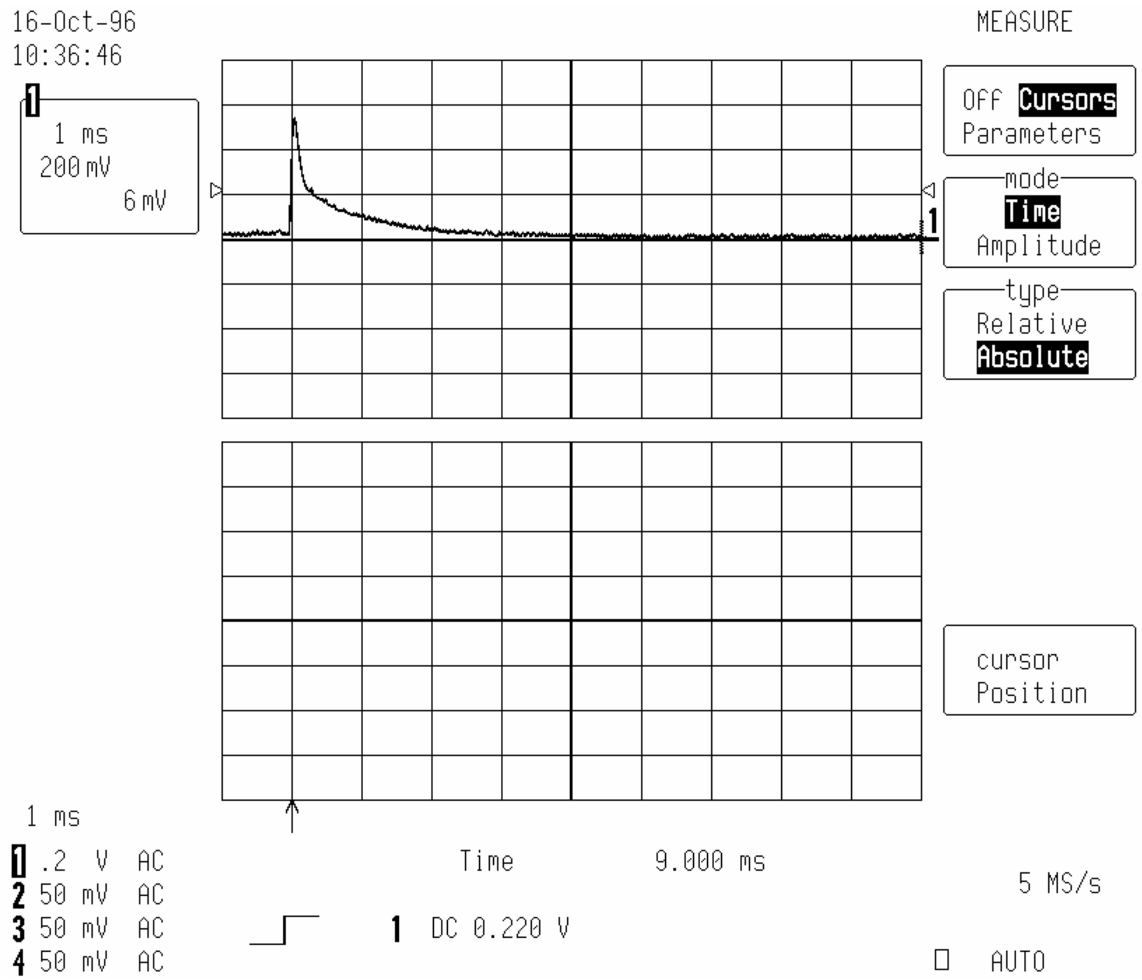

Figure 11: Sample Output with Test Signal

This feedback system is usually optimized experimentally. A square wave is injected into the system, and the frequency response is determined by the response of the system. Here, we see a response which is mostly completed in 0.1 ms (suggesting a 10kHz frequency response), with a tail that lasts a few ms. Such a response is characteristic of a properly operating hot film. Hot wires are similar but lack the tail, which is caused by the slow relaxation of the temperature distribution in the quartz substrate. For 520, it would be good to read the manual enough to figure out how to adjust the frequency response.

1.1.8 Reading A Micrometer

The pitot tube is mounted on a micrometer and is already positioned such that r=0 (center of tunnel) corresponds to the center "0" on the micrometer scale. The anemometer probe is also mounted on a micrometer.

On the micrometer each numbered mark represents 0.1 inches and each small mark represents 0.025 inches (see Figure 11-16.

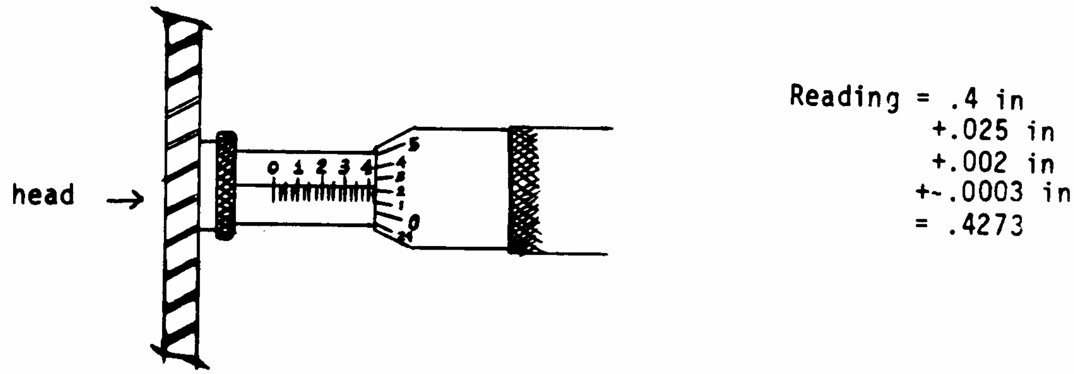

Figure 11-16

Thus if the indicator starts at 4 and moves one small mark, the head will move 0.025 inches. If the indicator starts at 2 and moves to 1, the head moves 0.1 inches. For 520, you will need this general approach to read the vernier on the traverse.

2 Lab Procedure

1.2.1 Prelab Preparation

If experimental data for V^2 is plotted against $\sqrt{U}$ a nearly straight line results,

$$\sqrt{U} = AV^2 + B$$

A method for obtaining the `best' fit for A and B is then required. If the observed points are (x_i,y_i), where i runs from 1 to n, one best fit y = mx + b is defined by minimizing the sum of the squares of the deviation of the fitted curve from the data. Thus, one minimizes

$$f(m,b) = \sum_{i=1}^{n} \left(mx_i + b - y_i\right)^2$$

It can be shown that minimizing *f* with respect to variations in *m* and *b* leads to the formulas

$$m\left(\sum x_i\right) + nb = \sum y_i$$

$$m\left(\sum x_i^2\right) + b\left(\sum x_i\right) = \sum x_i y_i$$

where all sums run from i=1 to i=n. Prepare yourself to compute the coefficients A and B which will be required for the experiment. This is called a least squares fit. Further information can be found in many math books.

1.2.2 Introduction

This experiment uses a hot film or hot wire. The constant-temperature anemometer used in conjunction with the hot film is essentially the same as one used with a hot wire. The TSI equipment used here can handle both types using a single instrument.

Part A: The hot-film or hot-wire anemometer will be initialized. The cold resistance will be measured and the operating resistance will be set.

Part B: A calibration curve will be obtained for the anemometer voltage as a function of velocity. To obtain meaningful velocity data the output voltage from the hot film anemometer must be related to a known velocity. To establish a known velocity a pitot-static tube is employed. Several different velocities will be established in the small wind tunnel. From the data for the anemometer voltage and the pitot-static pressure a calibration curve will be made.

1.2.3 Practice with Reading a Micrometer

The apparatus employed is the small wind tunnel equipped with a venturi meter. The pitot-static tube is mounted on a micrometer and is already positioned such that r = 0 (center of tunnel) corresponds to the center "0" on the micrometer scale. The hot film anemometer probe (henceforth referred to as probe) is also mounted on a micrometer (note reading on micrometer when probe is centered). The probe and the pitot-static tube micrometers are located on opposite sides of the wind tunnel, with the probe slightly upstream of the pitot-static tube.

The micrometer consists of three main parts, the head, the shank, and the handle. The pitot-static tube and the probe are connected to the head of two micrometers. The shank of the micrometer has a scale on it and the handle rotates and moves the head forward and backward. The pitot-static tube and the probe move with the heads. The handle also has a scale on it. The idea is that as the handle is rotated the head moves, the distance between the initial and final positions of the head can be determined by reading the scale.

Turn the handle until the front of the handle lines up with one of the scale marks on the shank. Now turn the handle slightly until the "0" on the scale on the handle lines up with the mark running the length of the shank. The handle should be positioned such that the front of the handle lines up with one of the scale marks on the shank and the "0" on the handle scale should line up with the mark running the length of the shank. If the handle is rotated one complete turn, the handle will move so that it is lined up with another mark on the scale. As the handle was turned, the head moved and as the handle moved from one scale mark to another (handle turned one complete revolution) the head moved 0.025 inches. The head either went forward or backward depending on which way the handle was turned. It takes four complete revolutions for the handle to move from one number scale mark on the shank to another. As the handle moves from one numbered mark to another the head moves 0.100 inches (4 x 0.025).

If the front edge of the handle is in between scale marks on the shank, then the reading on the handle scale indicates how far the head has moved since the front of the handle was lined up with last shank scale mark visible. If the front of the handle is lined up with a shank scale mark ("0" on the handle lined up with mark running length of shank) and the handle is turned until a 17 (an arbitrary number) on the handle scale lines up with the line on the shank, then the head is 0.017 inches from the position it would be in if the 0 on the handle scale were at the next visible mark on the shank scale.

Examine the micrometers and make sure you know how to read them.

1.2.4 Caution!

- The hot wire or film is easily burned out by excessive current or current spikes. Be careful to set the overheat correctly.
- **Make sure the anemometer is on STANDBY when disconnecting or reconnecting the probe.**

1.2.5 Part A: Anemometer Setup

1. Turn on the IFA. This device has flush mounted buttons, after each one is pushed a small tone will be heard.

2. Check the switches and connections on the back of the IFA: the hot film should be hooked to the `STD' connector, the signal conditioner on INTernal, coupling on DC, and the sensor switch set to `film'.

3. The probe cold resistance must be known, to set the anemometer overheat. Measure it using the low-current HP3478A. A normal hand-held meter uses too much current, and will destroy the wire. Record this cold resistance.

4. To find the operating resistance, multiply your cold resistance by an overheat ratio of 1.25 or 1.5.

5. Set this operating resistance on the IFA:

   a) Press: Operating Resistance (OPERATE RES)

   b) Turn the OPERATE RES knob until the display reads the desired operating resistance. CAUTION: DO THIS CAREFULLY. SETTING EXCESSIVE OVERHEAT WILL BURN OUT THE PROBE.

10. The Signal Conditioner will not be used for this experiment.

11. Press RUN/STANDBY (be sure red light next to RUN is on.) This sends current to the hot film. The anemometer is now running.

12. Check the anemometer signal on the oscilloscope to make sure it is not oscillating. What do the turbulent fluctuations look like? If you see high-frequency oscillations (above 50 kHz), you will need to adjust the “frequency compensation” controls - talk to your TA. The compensation is affected by both the “cable compensation” and bridge compensation” controls.

1.2.6 Part B: Setting up the Wind Tunnel

1. Examine how the following are connected:
   - Pitot-static tube to manometer.
   - Venturi meter to manometer.
2. For the above manometers do the following:
   - Level the manometers.

- Set manometers to some initial setting.
- Examine how the two sides of each manometer are connected.
- All manometers are scaled in inches of water.

3. The flow rate in the wind tunnel is controlled by the FLOW RATE DOOR which slides over the outlet of the fan. When the door is completely closed, the flow rate is small, but it is NOT zero. The only way to get a zero flow rate is to have the tunnel off. Watch your fingers when adjusting the flow rate door!
4. Set the probe and pitot-static tube symmetrically, 0.15 inches from the center of the tunnel, at which distance they are assumed to be far enough apart so as not to affect one another while giving identical velocity readings. The pitot-static tube should NOT be directly behind the anemometer.
5. Make sure the flow rate door is fully closed. This will protect the probe when the tunnel is switched on. DO NOT start the tunnel yet.
6. Switch the anemometer to Run. The output voltage is the voltage corresponding to zero velocity (free convection). The probe is now in the constant temperature mode. As the air velocity across the probe increases, the anemometer voltage will increase to maintain the hot film a constant temperature. A calibration curve will be made to show the relationship between air velocity and probe voltage.
7. Record INITIAL REFERENCE READINGS for the following:
   - Pitot-static tube manometer
   - Anemometer voltage
8. Making sure the flow rate door is closed, turn on the wind tunnel. Vary the flow rate by opening the door, and observe on the manometer the maximum and minimum dynamic pressure. Record these values. These values are just the maximum and minimum dynamic pressure which is available in the tunnel. The real minimum dynamic pressure is zero which is obtained when the tunnel if off. However, the physical mechanism for heat transfer from the wire changes from forced to free convection at very low speeds, so do not use hot-wire calibration data obtained at zero velocity! (How might you determine the lower limit at which the usual calibration is valid?)
9. Determine at least ten equispaced values of Δp between the max and min for your calibration points. Record these in your notebook in a table in the left hand column.
10. Using the flow control door, set dynamic pressure to the lowest value.
11. Record the following readings (after letting manometers stabilize):
    - Pitot-static tube manometer
    - Anemometer mean voltage (from meter on anemometer)
12. Repeat step 11 for each equispaced value of dynamic pressure.
13. Turn off the tunnel.
14. After allowing the manometers to stabilize, record FINAL REFERENCE READINGS.
15. Set the anemometer to STANDBY.
16. Now calculate the velocity U for the flow over the hot film, from the pressure readings. Tabulate $\sqrt{U}$ and V^2, where V is the voltage. (You may wish to do this and the following data analysis after the lab, if you are in danger of running out of time).

17. Plot $\sqrt{U}$ versus V^2. How well does the data fit a straight line? If any points are far off, this suggests that some kind of error may have been made.
18. Determine the best fit constants in the equation

$$\sqrt{U} = AV^2 + B,$$

using a least squares fit to the data (you should know how to do this from the prelab).
19. Now you have a procedure for obtaining U from V, which you will use later.