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AE3051 Experimental Fluid Dynamics

UNSTEADY VELOCITY MEASUREMENTS IN A JET USING A HOT WIRE ANEMOMETER

Objective

The objective of this laboratory experience is to familiarize the student with the theory and operation of a hot-wire/hot-film anemometer system, which is a standard technique for measuring fluctuating flow (gas) velocities. Here, the system will be used to measure the mean and root-mean-square velocity profiles across a jet of air. The jet is produced by the exhaust of a round pipe centered in a small, low-speed wind tunnel.

> *Note: the anemometer is a very* ***delicate and expensive device****. Please use* ***extreme care*** *in handling the probe and the sensor, and be sure to* ***read and understand the instructions*** *and the principles of operation well before you start the experiment! If you run into trouble****, do not turn any knobs on a trial basis****!* ***Ask for assistance****; the sensor and the instrument circuit can be quite easily burned out. The sensor is very fragile, so* ***do not shake it or touch i****t.*

Background

Rapid fluctuations in velocity occur in most flows of practical interest. Examples are: the boundary layer above wings and fuselage surfaces, the wakes behind obstacles in flows, jets from the nozzles of rockets and gas-turbine engines, and flows inside engine components. These fluctuations have profound effects on such things as drag, surface shear stress, boundary layer separation, mixing between fuel and air in engines, and vibrations of turbomachines and control surfaces. To understand such phenomena, we must be able to measure velocity fluctuations accurately.

There are several difficulties in making such measurements. First, we must find a sensor that has a measurable change in output for small changes in velocity (good signal *sensitivity*), and which will survive in a fluctuating flowfield (*robust*). Second, the device must respond faithfully, and perhaps without any time lag, to rapid fluctuations (good *temporal resolution* or good *high frequency response*). Third, the measurement device should not interfere with the flowfield and change the quantities being measured (*nonintrusive*). For a physical probe, this means it must be small or properly shaped. Fourth, the device must respond only to the velocity in a very small, and precisely known, region (good *spatial resolution*).

Hot Wire/Film Description

The hot wire is a delicate device that provides velocity data (under certain limitations). Its small, almost "microscopic" size gives it good spatial resolution and high frequency response. In addition, it is highly sensitive. The sensing element is a long circular cylinder, typically a tungsten or platinum wire of diameter in the range of 5 to 20 µm (2-8 $\times 10^{-4}$ inches). Slightly more rugged hot-film sensors are also commonly used. These are glass rods, ~50 µm in diameter, with platinum films, typically 10 Å thick (Å = Angstrom = 10^{-10} m), coated on the surface. In either case, the wire or the glass rod is fixed to two gold-plated steel needles which serve as the electric contacts to the sensor. The wire or film is kept heated by an electric current, to temperatures of 200 to 300 °C (and sometimes up to 800 °C). When air flows over the wire, energy in the form of heat is carried away by the much colder air stream (*forced convection*) because of the temperature difference between the (hot) sensor and (cold) air. A typical probe and a flow pattern over a sensor are shown in Figure 1. The sensor is so small that the Reynolds number of the flow is usually very low, and so the flow pattern over the sensor can be assumed to be symmetrical and quasi-steady,[1] as shown in the figure.

Heat Transfer Analysis

The length of the sensor wire (or rod) is much greater than its diameter. Hence, it may be assumed that heat losses by conduction[2] through the ends are negligible, and the relations for heat transfer from an infinite cylinder may be applied. However, note that not all of the length of the wire is actually used as the sensor. In fact, the wire (or rod) is coated with a relatively thick layer of highly conductive gold or silver, except for a small length at the center. This center portion has a significant electrical resistance and acts as the sensor. Thus, the spatial

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[1] In this case, quasi-steady means that the flow changes slowly compared to the rate at which the heat transfer processes can adjust. Therefore a simple steady-state analysis can be performed. The smaller the probe, generally the faster the heat transfer processes can adjust.

[2] Conduction is heat transfer through the material by diffusion, e.g., in one-dimension the heat flux (energy per unit time per unit area) is governed by the equation $dq/dt = -k(dT/dx)$.

resolution of the sensor is kept high.

The convective heat transfer rate, $\dot{Q}_{conv}$ (e.g., Watts or Joules/second) for a flow is generally given by an expression of the form $\dot{Q}_{conv} = hA_s(T_s - T_f)$, where h is a *convective heat transfer coefficient*, A_s is the surface area of the body gaining/losing energy, T_s is the temperature of the surface and T_f is the temperature of the fluid flowing over the body. For a cylinder in cross-flow (flow perpendicular to the axis of the cylinder), the solution for the convective heat transfer coefficient leads to the following expression for the rate (with subscripts substituted for our conditions),

$$\dot{Q}_{conv} = (A + Bu^n)(T_w - T_a) \tag{1}$$

where T_w is the temperature of the wire, T_a is the temperature of the air, and u is the mean velocity of the air flow.

The values A, B and n are constants, valid for a given value of T_w, T_a and a given wire. They can be determined by calibration of the sensor. Physically these constants include the effects of such things as the thermal conductivity of the sensor, the Nusselt number of the flow, and the size of the sensor. Unless one is researching the construction of these probes, it is not usually easy to calculate from first principles the sensitivity of a given sensor, since the property values will depend strongly on the manufacturing processes used. So, it is far easier to obtain A, B, and n by calibration against some other velocity standard, for example a Pitot-static probe, in a simple, nearly steady flowfield.

The sensor, whether it is a wire or a film, is by far the largest electrical resistance in the probe. Thus, the electric power dissipated as heat in the sensor, $\dot{Q}_{elec}$, (which is the reason for its being hotter than the surrounding air) is given by

$$\dot{Q}_{elec} = I^2 R_w \tag{2}$$

where I is the current passing through the sensor, and R_w is the resistance of the sensor.

For steady-state operation, i.e., the sensor temperature is constant and the air velocity is constant, the rate of the electric power dissipation equals the rate of convective heat transfer. That is equating equations (1) and (2),

$$I^2 R_w = (T_w - T_a)(A + Bu^n) \tag{3}$$

Using Ohm's Law on the circuit shown in Figure 2,

$$E^2 R_w = (R_3 + R_w)^2 (T_w - T_a)(A + Bu^n) \tag{4}$$

where E is produced by a voltage (**E**lectromotive Force) source, and R_1 and R_3 are resistors that are made from material whose resistance does not vary with temperature. Thus, we see that if R_w and $(T_w - T_a)$ are held constant, **E^2 increases with u^n**. This fact will be used in calibrating and using the instrument to measure velocity.

Constant Temperature Anemometry

As noted above, the sensor is typically made of platinum or tungsten. These materials have the property that their electrical resistance increases linearly with temperature. In other words, their resistance can be described by

$$R_w - R_0 = R_0\, \alpha\, (T_w - T_0) \tag{5}$$

where R_0 is the value of the resistance at a reference temperature T_0 (room temperature, for example), and α is the "temperature coefficient of resistance". For platinum in wire form, this coefficient is approximately 0.0024/°C. Unfortunately, for platinum films, as used in commercial hot-film probes, no such uniform value can be given. Examination of the factory calibration values written on the sensor box will show different values of α for different sensors. *The value for the particular sensor to be used in the experiment must be noted.*

When the current through R_w is increased, more heat is produced. If this is not convected away at a high enough rate, T_w will increase, until the difference $T_w - T_a$ becomes large enough for the convection rate to equal the heating rate.

The circuit shown in Figure 2 is called a Wheatstone Bridge. When R_1=R_3 (i.e., on the 1:1 bridge setting), the circuit is said to be *balanced* when the voltage across M-N is zero. This occurs when the resistance R_w is equal to the variable resistance R_B. On the anemometer control panel, when you turn the dial to “set” the operating resistance, you are actually changing the value of R_B. If R_w is lower than R_B, the resulting “unbalance” voltage at M-N is measured by the anemometer electronics and is amplified by a feedback circuit such that the voltage E increases. This produces a higher current flow through the sensor, also increasing its temperature and resistance. Thus, when you set the operating resistance (by actually setting the balance resistor) and turn on the circuit (go to “RUN” with the front-panel knob), **the**

voltage E rapidly rises to some high value. If you set R_B at too high a value, and go to "RUN", the current through the sensor will rise to a value so high that the sensor may overheat and melt. Typically, the resistance of the wire or film is set to a value 1.3-1.7 times its room temperature resistance (the ratio of the operating to room temperature resistance is known as the *overheat ratio*), in order to achieve a sufficiently high operating temperature for the anemometer.

Once a desired value of R_w (and T_w) has been reached, the feedback circuit is used to keep the resistance R_w fixed. If the air velocity increases, for instance, the heat transfer rate increases. The circuit responds quickly[1] by increasing the voltage across R_w, and hence the current through R_w, to keep its temperature constant. The resulting change in the voltage E is measured, and is used to calculate the change in air velocity.

Calibration

Each hot-film probe has to be calibrated against some known velocity measurement. For example, this can be accomplished by locating the hot wire sensor near (but not close enough to be affected by) a Pitot-static probe in a sufficiently uniform and nearly steady flow. A value of R_w, typically 1.5-2 times the sensor resistance at room temperature, is set, and the feedback circuit is activated. The flow velocity is varied in steps over the range of velocities expected in the actual experimental flowfield of interest. At each velocity setting, the velocity measured by the Pitot-static probe is recorded, as well as the voltage E from the anemometer.

From Eq. 4, the voltage - velocity relation may be written as

$$E^2 = C + Du^n \tag{6}$$

where C, D, and n are constants for a given sensor, operating at a given value of resistance, in a flow of constant temperature, density and composition. A plot of the voltage E against the mean velocity u should look somewhat like Figure 3(a), whereas a plot of E^2 against u^n should be a straight line, as shown in Figure 3(b). The constants C, D and n can be determined using regression analysis.[2] *[In this lab, the computer will record both the Pitot output (converted by*

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[1] The response time for a typical hot-wire anemometer system is on the order of 10 μs; thus it can faithfully record velocity fluctuations with frequencies up to ~100 kHz.

[2] You can use a simple linear regression analysis (which is a two parameter fit to match a straight line to data). Try different values of n (usually near 1/2), and for each n, find the intercept (C) and slope (D) of the line that gives the best straight line fit of u^n against E^2. Then pick the best n, C, D combination (best overall fit).

the computer to a speed measurement using the Bernoulli equation applied to the voltage output of the Baratron transducer) and the hot wire voltage output.] Note that the values of C and D include quantities such as the resistance values. As long as you do not plan to change the resistances during the experiment, this is satisfactory. Normally, if the room-temperature resistance of a sensor starts changing, it means that the sensor is failing. Obviously, if you have to change sensors during an experiment, you will have to calibrate the new sensor before you can interpret its signal.

Turbulent (and Fluctuating) Flows and Data Reduction

Velocity Decomposition

Turbulent flows are not only unsteady, but chaotic in character.[1] The turbulent flows in which hot-wire/film anemometers can be used are usually those in which the fluctuations in velocity are small compared to the mean velocity. Thus, we decompose the instantaneous velocity u(t) as follows

$$u(t) = \overline{U} + u'(t) \tag{7}$$

where $\overline{U}$ is the mean velocity and u' is the fluctuating component (with $u' << \overline{U}$). These may be seen from Figure 4, which illustrates how the velocity at some point would change with time in a turbulent flow.

The data acquisition system will sample the voltage, and record the instantaneous voltages (E), which are proportional to the instantaneous current through the hot-wire/film. Note that the time average of the fluctuating component, $\overline{u}'$, should be zero since the fluctuations are random and the u' at any instant is as likely to be positive as negative. However, the variance $\overline{(u')^2}$ is not zero, and gives us a measure of the intensity of the fluctuations. The positive square root of the variance is called the root-mean-square, or RMS for short. The variance of the velocity enters directly into the time-averaged Navier-Stokes equation (AE 2020 and AE 3021). This quantity will be calculated and used here.

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[1] For background material on turbulent flows, you may wish to read Anderson's *Fundamentals of Aerodynamics*, 1984, Chap. 16, or Kuethe and Chow, *Foundations of Aerodynamics*, 4th Ed., Sections 18.1 - 18.3.

Calculating Velocity Fluctuations from Hot-wire Voltages

We have already seen that the feedback circuit and the very small size of the sensor combine to allow the instrument to react rapidly to changes in flow velocity by changing the voltage across the sensor. Thus the primary use of a hot-wire or hot-film anemometer is to measure velocity fluctuations with very rapid response. The sensitivity of the anemometer to small changes in velocity can be determined by applying some simple calculus. Differentiating Eq. 6,

$$2EdE = nDu^{n-1}du \tag{8}$$

Then, using Eq. 6 to replace u,

$$2EdE = nD^{1/n}\left(E^2 - C\right)^{\frac{n-1}{n}} du \tag{9}$$

For the decomposition of Eq. (7), a small velocity fluctuation u' about $\overline{U}$, there will be a corresponding voltage fluctuation e' about the mean voltage $\overline{E}$ (i.e., $E=\overline{E}+e'$). The velocity and voltage fluctuations can be related for the case of small fluctuations[1] from Eq. 9 with the substitutions $dE \rightarrow e'$, $du \rightarrow u'$, $E \rightarrow \overline{E}$ such that

$$u' = \left[\frac{2\overline{E}}{\left\{nD^{1/n}\left(\overline{E}^2 - C\right)^{\frac{n-1}{n}}\right\}}\right]e' \tag{10}$$

Thus, if the calibration of the probe is known, the relation between the fluctuating component of the voltage and the fluctuating component of velocity can be calculated. If one did not record the complete time-dependent voltage signal, but instead only recorded the mean and root-mean square voltages, then the RMS velocitiy could be obtained from the measured RMS voltage with,

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[1] If the velocity fluctuations are not small compared to the mean velocity, it is not accurate to make these substitutions and a more complicated approach is required.

$$u_{rms} = \left[\frac{2\overline{E}}{\left\{ nD^{1/n} \left(\overline{E}^2 - C \right)^{\frac{n-1}{n}} \right\}} \right] e_{rms} \tag{11}$$

where the mean and rms voltages can change between each measurement location.

Filtering and Signal Dynamic Range

A problem can occur if the voltage fluctuations are very small compared to the mean voltage. Since an analog-to-digital converter (ADC) has a limited dynamic range, it may be unable to accurately measure both the average (large value) and fluctuating (small value) components. For example, to distinguish between 4.999 and 5.000 volts requires a dynamic range of at least 5000 (and therefore at a minimum a 13-bit ADC, 2^{13}=8096). Use of a lower dynamic range system can cause significant errors in the value of the RMS. One solution is to subtract out the mean of the voltage signal *before* sampling it, and then amplifying the remaining fluctuations to make use of the full range of the ADC converter. This can be done using an analog (high-pass) filter and an amplifier.

In your experiment, two circuits will be used to measure the instantaneous output voltages from the hot-film bridge electronics. The raw voltages from the anemometer are sent to a digital multimeter (**DMM**) for visual inspection. The DMM provides a visual indication of the mean voltage (the numbers change so slowly that it will not show the fast fluctuations). In parallel, the anemometer output is sent to the computer (to **one input channel**) and to a **high-pass filter**. The high-pass filter is used to eliminate the mean value, $\overline{E}$, leaving only the fluctuating component e'. This is accomplished by setting the high-pass filter to pass any fluctuations in the signal above a few Hertz, effectively removing the DC (zero frequency) content of the signal.

Next, the output level from the high pass filter is increased by an **amplifier** so that it better matches the maximum voltage range of the ADC. The amplifier multiplies the high-pass filter output by a **gain**. For example, if the gain of the amplifier is 200, then the amplifier's output voltage is $200e'$. The output of the high-pass filter is sent in parallel to an **oscilloscope** and a **low-pass filter**. We use the filter to remove frequency content above the Nyquist limit in order to prevent aliasing in the power spectrum. (Recall this is important if one is interested in determining the frequency content of the signal, which you will do as you will be observing power spectra on the computer based on this signal.) You might remember, the filter does not have a sharp cutoff response; it has a “roll-off” like that measured in an earlier lab. The filtered signal is then sent to the computer data acquisition system (**second input channel**).

The oscilloscope is used to observe the peak-to-peak fluctuations, in order adjust the amplifier gain. The gain should be as high as possible without the signal extending beyond a range of about -4 to 4 V. The Krohn-Hite filters you will use can not produce outputs above ~4.5 V (they saturate, meaning any more increase in the input does not produce a higher output). Thus the input signal to the low-pass filter must not exceed this range.

Measurements in a Jet

One feature of the hot-wire anemometer to bear in mind is that one should have a good idea of the structure of the flowfield before attempting to make measurements with it. Very precise measurements can be made by a careful and alert experimentalist, but not without some consideration of the flowfield. Figure 5 shows a schematic of the flow set-up for this laboratory. A circular pipe brings air output from a centrifugal blower to the upstream edge of the wind tunnel test section. The flow comes out of the pipe as a jet, with a velocity different than that of the test-section freestream. A fan downstream of the tunnel diffuser creates a pressure difference that induces the tunnel freestream, and forces it out of the laboratory.

As shown in Figure 5, the jet flow leaves the pipe with a (typically) high velocity. At the edges of the jet, the effect of viscosity causes the surrounding test section flow to accelerate, and the jet flow to decelerate. In fact, the flow at the edges of the jet is forced outward as it is “pulled” by the slower-moving test section air. Thus, some of the jet flow “rolls up” into vortex rings around the jet, so that some air that originated in the test section flow goes into the jet, and vice versa. Thus, there is a *mass transfer* and *momentum transfer* across the jet boundaries. Things rapidly become confused and unsteady at the jet edges, so that the velocity fluctuates. The fluctuations are largest inside the ***shear layer*** at the edges of the jet. Near the center of the jet, there is still a region where the fluctuations have not reached. This is called the ***potential core***, and the fluctuation level should be quite low here. The shear layer grows quickly, so that the potential core rapidly disappears as the jet goes downstream. At the same time, the mass and momentum transfer force the time-averaged velocity profile across the jet to become smoother and to gradually disappear, as the jet merges with the test section flow. *You can acquire velocity data along a vertical line extending from somewhere below the top wall to a region below the centerline of the jet.* This line is nominally near the horizontal center of the jet and near the end of the test section.

The two anemometer outputs, nominally E(t) and e′(t)×amplifier gain, are connected to the computer, as is the output from a Pitot probe (located at a fixed point in the test section). The computer output data file will contain values of vertical location of the measuring point (y), and the mean and rms voltages for all three signals: the Pitot probe, the unfiltered input, and the low+high-pass filtered data, as well as the gain of the amplifier used for each point. *The gain is already accounted for (i.e., removed) by the software in the high-pass filtered results (e.g., the computer outputs* e_{rms}), *and is included in the file merely for information and a point of discussion.* You can convert the hot- film readings to velocity results using Eqs. 6 and 11, and the calibration constants.

Preliminary

The following items must be turned in at the start of your lab session.

1. Assuming the maximum *average* velocity, $\overline{U}$, in the jet is around 40 ft/s, bring a list of 10 velocities you would pick for calibrating the hot-wire (remember, the hot-wire output voltage *is not a linear function of velocity*, therefore equally spaced velocities are probably not a good idea). Choose a set of velocities to cover the entire range from the lowest to highest *instantaneous* values you expect to see during the experiment (also be aware that velocities below ~10 ft/s will be difficult to measure with the Pitot probe). The linear regression procedure will not work unless you have *at least* two values of velocities that are near the low end.
2. Construct a wiring schematic (**circuit diagram**) for this lab based on the information presented on pages 8-9 and item 2 of the Procedure. Starting with the output signal of the anemometer and ending with all inputs to the data acquisition system, oscilliscope and the DMM.
3. In addition, bring a (corrected?) copy of the equation you developed in the earlier labs for the dynamic pressure (**mm Hg**) as a function of ambient pressure (**in. Hg**) and temperature

(**°F**), and velocity (this time in **ft/s**). You will be using it to set the tunnel at your chosen calibration speeds.

Procedure

Preparing the Hotwire

1. Note down the sensor and probe resistance values given on the sensor box for your sensor (you will need them in step 6 below). This includes the resistance at some reference temperature, the change in resistance across some temperature range, and the suggested operating resistance.
2. **Circuit diagram** - make (or if already made, check) the data acquisition circuit connections, i.e., connect the filters, amplifier, etc. as noted above (see the Filtering and Signal Dynamic Range section on page 8). Make sure that the Pitot-static probe voltage is connected to channel 0 of the computer data acquisition system (i.e., *analog input channel 0*), the unfiltered hot-wire bridge output is connected to channel 1, and the filtered hot-wire is connected to channel 2. Also make sure the digital input/output (DIO) channels 0 and 1 are connected to the vertical stepper motor controller (channel 0 is up, channel 1 is down).
3. Manually run the actuator, mounted to the large traverse table, to its maximum “up” position in the wind tunnel using the stepper motor controller.
4. *Have the TA’s turn the laser on* so that you can adjust the vertical position of the hot-wire probe to nearly match that of the focused laser beams (you are doing this so that the data you acquire in the following LDV lab, can be compared to the data collected from the hot-wire). Also try to note the difference in transverse (side-to-side), and downstream position of the laser focus and the hot-wire. **DO NOT LET THE LASER HIT THE PROBE - REFLECTIONS FROM LASERS CAN BE DANGEROUS.**
5. Locate the **Instruction Sheet** for the anemometer. Be sure the anemometer is on STANDBY, with METER SWITCH set to BRIDGE voltage, selector switch to 5:1 BRIDGE Voltage.
6. Your goal in this step is to determine the balance resistor setting that will make the hot film operate at the suggested resistance (found in step 1). To do this, you need to

determine the combined resistance of the probe holder and cable connecting the control unit to the probe holder. You do this by first measuring the combined resistance of the cable, probe holder, probe and sensor (the hot film) at room temperature as specified on the **Instruction Sheet**. As indicated there, this is accomplished by “balancing the bridge.” The resistance of the probe holder and cable are found by subtracting the room temperature resistance of the probe and sensor (found from the values determined in step 1) from the total resistance you measured by balancing the bridge.

7. In order to set the sensor resistance to its high temperature value for operation, you need to set the balance resistor on the anemometer control unit to the sum of the suggested operating resistance (this is for the combined sensor and probe, again from the values found on the sensor box) and the resistance you determined for the cable and probe holder.

Calibration of the Hotwire

8. During calibration of the wire, you will vary the tunnel speed setting in steps (based on the list of velocities you brought to the lab – or an updated version). The “true” velocity will be measured with the Pitot-static probe. Calculate the dynamic pressures in terms of Baratron voltage outputs (which you will set using the voltmeter) that correspond to the tunnel freestream velocities that you want to use.
9. With the sensor close to the Pitot-static probe tip, and aligned perpendicular to the flow direction, **start the tunnel**. Put the Anemometer circuit on RUN by following Part C of the instruction sheet. Watch what happens to the mean voltage reading on the DMM.
10. Use the Labview VI to acquire the calibration data (this involves a different VI than you will use for the velocity profile across the jet). These data are recorded by the computer so that you can create the calibration curves required under “Data Reduction”. The calibration VI will save the Pitot speeds (ft/s) and corresponding hot-wire voltages.

Jet Measurements

11. Set the wind tunnel freestream velocity and the jet velocity at the values that you want (you might ask the TA’s for guidance). Realize that you will have to try to recreate these values in the LDV lab, which *will not include a Pitot-probe* for setting the freestream speed. **Therefore you should pick settings on the blower and fan controls that are easy to reproduce.**

12. Determine **ten** measurement locations across the flow at which you want to take data. Your first point should be at the highest vertical location, where the traverse hits its stop (this is near, but not at the upper wall). The maximum distance the traverse will move downward from this point is nearly 4.2 inches. To find interesting locations, you may wish to manually traverse the hot-wire and note the relative change in mean and rms velocities (using the DMM and oscilloscope) as the hot-wire moves across the flow.
13. Move the traverse up until it hits its stop and make sure the stepper motor controller is set to "computer."
14. Start the data collection VI and set the data acquisition parameters: sampling rate, duration - how many seconds to acquire data at each location, the voltage range for the ADC (the normal default voltage range is –10 to 10 V), and the measurement locations. Choose a sampling rate sufficiently fast to faithfully capture most of the high frequencies you might expect in this turbulent jet flow (the flow probably contains interesting information at frequencies up to no more than 7-10 kHz). Also choose your sampling parameters to produce a frequency resolution of 2 Hz or better. Make sure the power spectra is set to decibel (dB) scaling. **Make a note of these acquisition settings** (except for the measurement locations, which will be in the saved data file).
15. Set the cutoff frequency of the high-pass filter as low as possible, and that of the low-pass filter at an appropriate value based on the sampling rate chosen in the step above. **Make a record of these values**.
16. Set the NEFF amplifier gain so that the fluctuation range of the signal (seen on the oscilloscope) is as large as possible without ever exceeding the maximum voltage range of ~ –4 to 4 V. **This step of setting the amplifier GAIN will need to be repeated at every measuring station**.
17. Have the computer measure hot-wire data at each location (they will be stored by the computer later). Also **watch carefully on the screen the histogram and power spectrum** of the probe voltage and how they vary as the probe moves across the flow. For example from the histograms you can observe whether the velocities are distributed normally (bell curve), or if they have long tails on one side only. From the spectra, you can observe how the power in the turbulent fluctuations vary with frequency – where is most of the

turbulent energy. These types of observations on the histograms and spectra might deserve comment in your lab report.

18. When you are done, save the data. The LabView program will ask what types of data you want to save. There are four types: mean and rms voltages (denoted *final*), the instantaneous voltage readings (denoted *raw*), *histograms*, and *power spectra*. **At a minimum, save the *final* and *raw* data**. Then go back and repeat (5 more times each) the measurements at two locations to determine the repeatability of the data. One point should be *near the center of the jet*, and the other should be in the *shear layer* region between the jet and freestream. Save this new data – at minimum save the *final* and *spectra* this time.
19. At the end of the test, **return the probe to "STANDBY"**. Shut down the tunnel.

Hotwire Check

20. Repeat your measurement of the cold resistance of the sensor (to see if it changed). You might use the value you already measured as your starting guess in the procedure (Part A of the Instruction Sheet).

Data to be Taken

1. A sketch of the data acquisition circuits (**circuit diagram**).
2. Sensor cold resistance, probe resistance, cable and sensor holder resistance, sensor and probe operating resistance, operating resistance for the balance resistor, and the anemometer offset voltage (the voltage the hot wire bridge output reads before the circuit is turned to "RUN").
3. Computer data acquisition settings for the calibration measurements: sampling rate, sampling duration (seconds).
4. The computer will record the mean Pitot-static results (velocities in ft/s) and hot-wire voltages for the calibration. You may find it helpful to note the calibration constants it determines from these values (your values may differ when you perform your own calibration fit).
5. The tunnel and jet speed settings (where you set the motor control knobs) for the jet survey.

6. Computer data acquisition and filter settings for the jet measurements: sampling rate, voltage range, sampling duration (seconds), and the cutoff frequencies of the low- and high-pass filters.
7. During the jet survey, the computer will save the coordinates of the measuring locations, NEFF amplifier gain, and the mean and rms voltages from both the unfiltered and filtered anemometer signals in the *final* data file. The computer will also save (if asked) the instantaneous (*raw*) data, *histograms* and *spectra* at each measurement location in these respective files. **You need to record manually** the peak-to-peak values of the fluctuating signal on the oscilloscope for each measurement.
8. The measurement of the combined cold resistance of the sensor, probe, probe holder and cable at the end of the experiment.

Data Reduction

1. Determine **your own** calibration constants from the velocity and hot wire voltage data. (e.g., perform your own linear regression analysis).
2. Convert the mean and root-mean-square voltage values at each location to velocity values as described in this manual [see the section, Turbulent (and Fluctuating) Flows and Data Reduction).
3. Convert the instantaneous (unfiltered) voltage data at a location close to the jet centerline to instantaneous velocity data, and determine the rms velocity directly from this reduced data set.
4. For the repeated data locations, take the individual frequency spectra and convert them to average power at each frequency.

Results Needed for Report

1. The data acquisition circuit diagram.
2. A table containing the data acquisition parameters used for the calibration measurements.
3. A table of the calibration constants of the probe determined after the lab *by you*, *in appropriate units*.

4. Plot of the nonlinear calibration curve. The nonlinear calibration curve of the probe is the acquired calibration data with velocity as the abscissa (horizontal axis), and anemometer mean voltage as the ordinate.
5. Plot of the linear calibration curve. The linear calibration curve combines the measured data (U^n as the abscissa and E^2 as the ordinate) with the calibration line determined by your calibration constants.
6. A table containing the computer and filter data acquisition parameters used for the jet measurements.
7. A plot comparing the root-mean-square velocity fluctuation across the jet, as determined from both channels. That is from the unfiltered hot-wire data, and the data that was bandpass filtered. Also include the rms velocity at the point near the jet centerline that you calculated from the (reduced) instantaneous velocity data.
8. A plot of the normalized mean velocity profile across the jet. Plot $\overline{U}/U_\infty$ as the abscissa, where U_∞ is the value of $\overline{U}$ in the free stream of the wind tunnel. Take measurement location as the ordinate.
9. A plot of the variation in *normalized* root-mean-square velocity fluctuation (usually denoted the ***turbulence intensity***) across the jet. Plot the turbulence intensity *normalized two ways*: **1)** u_{rms}/U_∞ where U_∞ is the nominal velocity of the wind tunnel free stream and **2)** $u_{rms}/\overline{U}$, meaning the rms velocity at a measurement location normalized by the mean velocity at the same location. Use the measurement location as the ordinate. Include error bars for the locations at which you repeated the measurements.
10. Average power spectra (dB versus frequency) at the repeated measurement locations.

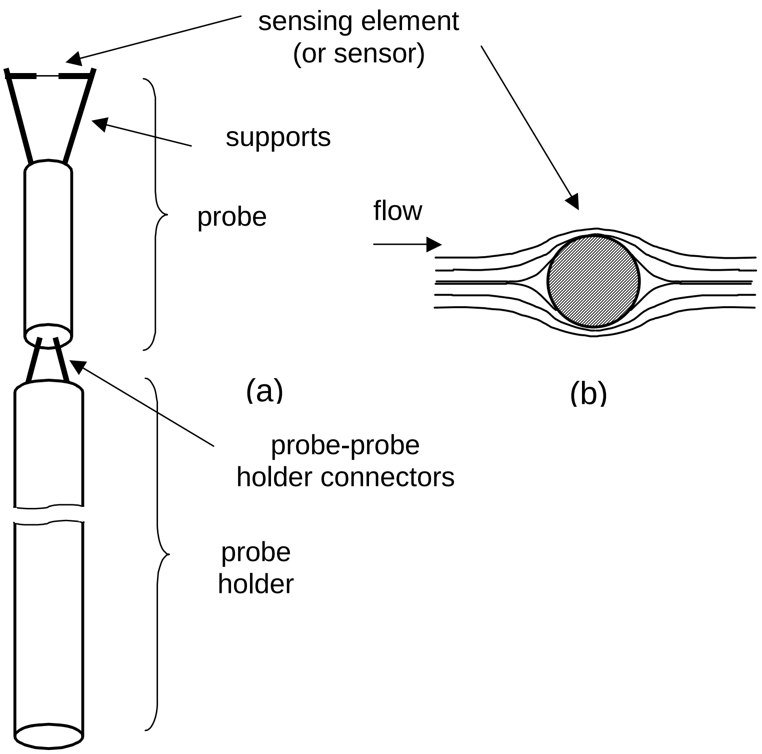

Figure 1. (a) Hot film sensor, and its support structure; (b) schematic of flow over the sensing element.

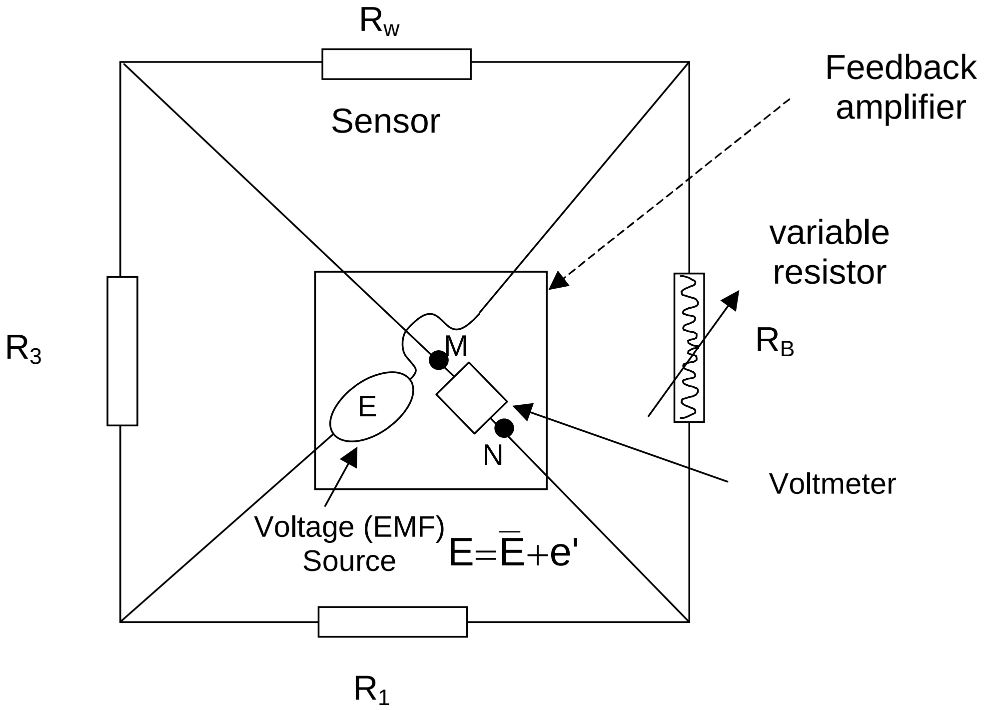

Figure 2. Constant temperature anemometer electronic circuit.

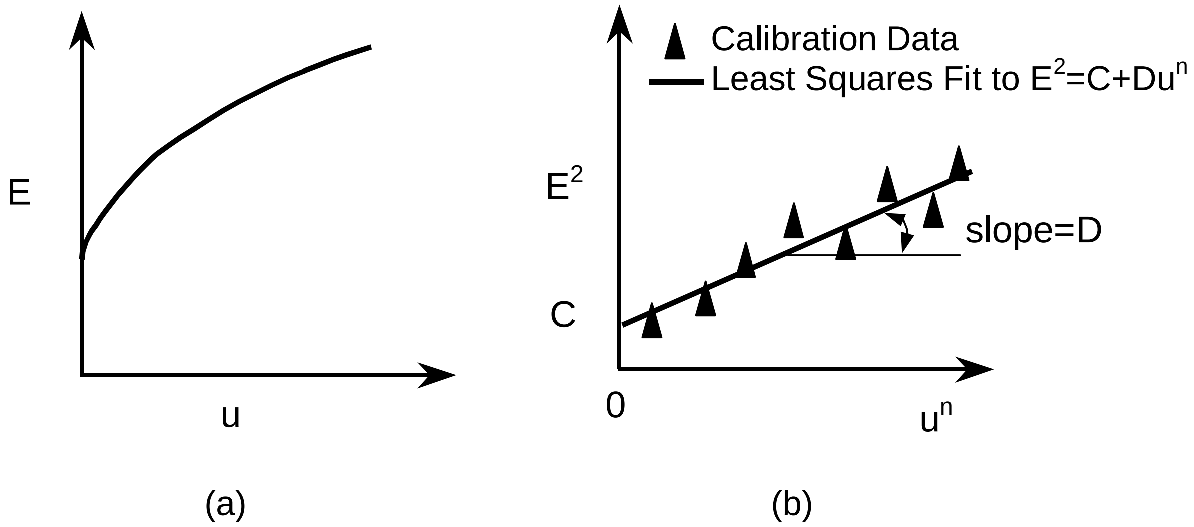

Figure 3. (a) Typical voltage-velocity relation for a hot-wire or hot-film anemometer (with n<1); (b) typical calibration curve to determine the constants C, D, and n.

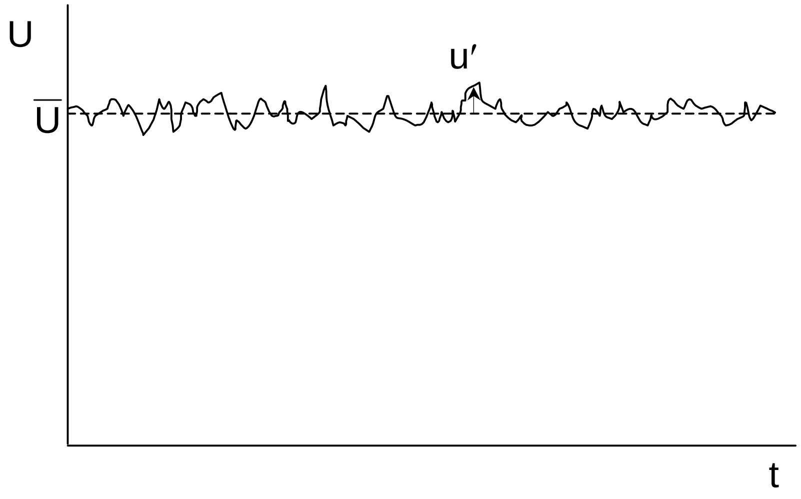

Figure 4. Typical velocity history at a single point in a turbulent flow.

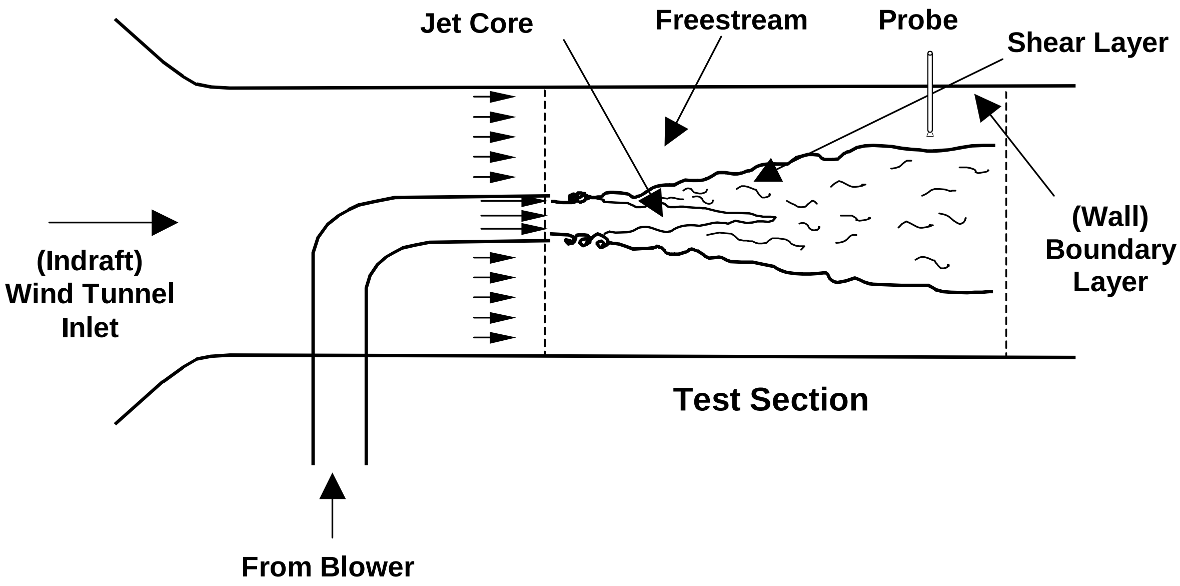

Figure 5. Schematic of jet flow in the wind tunnel.