# 1. HOT WIRES, WAKES, AND DRAG MEASUREMENT

## *1.1 Background*

### 1.1.1 Objectives:

In this experiment you will:

1. Learn about the structure of a wake.
2. Learn to calculate the drag on a body using the velocity profile of the wake.
3. Obtain experience in using a hot-film or hot-wire anemometer.
4. Compare results from various cylinder and airfoil wakes, under downstream conditions.

This experiment is adapted from a similar experiment in AAE333L. For 520, the detailed instructions given here will aid the beginning experimentalist in setting up the equipment. A number of new model positions have been provided, to permit carrying out a wide variety of experiments. Considerable additional time is also available. This should provide the 520 student with a problem that is sufficiently open-ended to allow room for senior/graduate level independence and creativity. The apparatus enables more experiments than you will have time to complete or analyze; select a focus from among these experiments for the work of your own group.

### 1.1.2 Specific Applications:

Wakes are extremely common and usually turbulent. The drag of airfoil sections is usually determined using wake surveys similar to the one performed in this lab.

### 1.1.3 Introduction

A wake is the flow pattern that develops behind an object as the object moves relative to a real fluid. The wake is observed to form behind moving bodies at all speeds (except at $Re < 1$), and all flow regimes. It one of the most fundamental flow configurations in fluid mechanics. Its importance is due to a variety of phenomena that have scientific as well as practical interest.

In the following description, we will examine the specific case of the wake behind a cylinder. However, this does not limit the scope of our discussion concerning the fundamental processes in the wake. The cylinder is chosen because it has been investigated extensively by theory and experiment. The cylinder is a good example of a bluff body, which causes massive separation on the lee surfaces.

The character of the flow behind the cylinder depends on the Reynolds number. The flow patterns that develop in the wake at different Reynolds numbers will now be discussed.

### 1.1.4 The Laminar Wake

At very low Reynolds numbers ($Re < 1$) the streamlines close behind the cylinder (no separation occurs). The flow is symmetrical fore and aft and therefore no wake is formed (Figure 1A).

At higher Reynolds numbers ($Re \geq 1$) the streamlines no longer close and a wake is formed behind the moving body. As will be discussed later in more detail, the velocity in the wake is smaller than the uniform free stream velocity. This velocity deficit is associated with the drag acting on the body. By measuring the velocity distribution in the wake we can estimate the drag on the moving body.

In the range of Reynolds numbers between 3 and 6 a pair of stationary vortices, called Foppl vortices, are formed behind the cylinder (Figure 1B).

At still higher Reynolds numbers the vorticity behind the cylinder increases as the pair of vortices moves downstream and elongates (Figure 1C). Finally, at Reynolds numbers of about 35 to 40 the vortices are periodically shed behind the cylinder, thus forming the well known von Karman vortex street consisting of two rows of vortices equally spaced and arranged with each vortex located at the center of the two vortices of the opposite row (Figures 1D and 1E). The shedding of the vortices is due to an instability which develops in the flow.

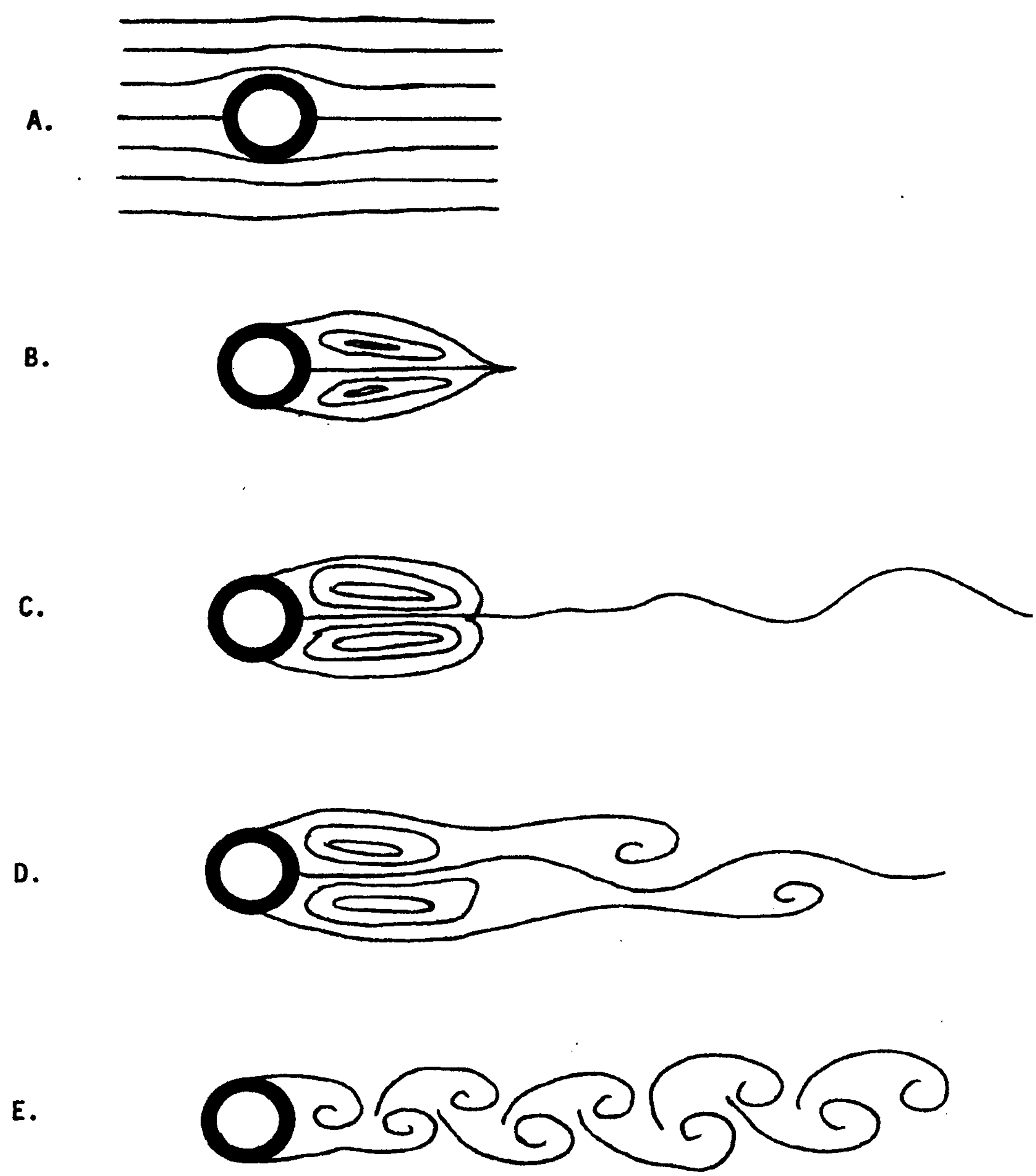


**Figure 1. Flow Patterns in the Wake of a Circular Cylinder.  Flow is from Left to Right.**

To describe these oscillating flows we introduce a nondimensional number called the Strouhal number.  The Strouhal number, S, is defined as:

$$S \equiv \frac{df}{U_\infty}$$

where f  is the shedding frequency of the vortices, from one side of the cylinder, d is the diameter of the cylinder, and $U_\infty$ is the free stream velocity.

The Strouhal number is the nondimensional expression for the ratio of the vortices' shedding frequency, f, over the characteristic flow frequency, $U_\infty/d$.  When describing oscillating flows, the Reynolds number alone is not sufficient to characterize the flow, since it contains no information about the oscillations. A second similarity parameter, the Strouhal number, must be used in order to describe the oscillation.

The change of the Strouhal number as a function of the Reynolds number is shown in Figure 12-2. The velocity $U_\infty$ can be calculated by measuring the shedding frequency of the vortices.

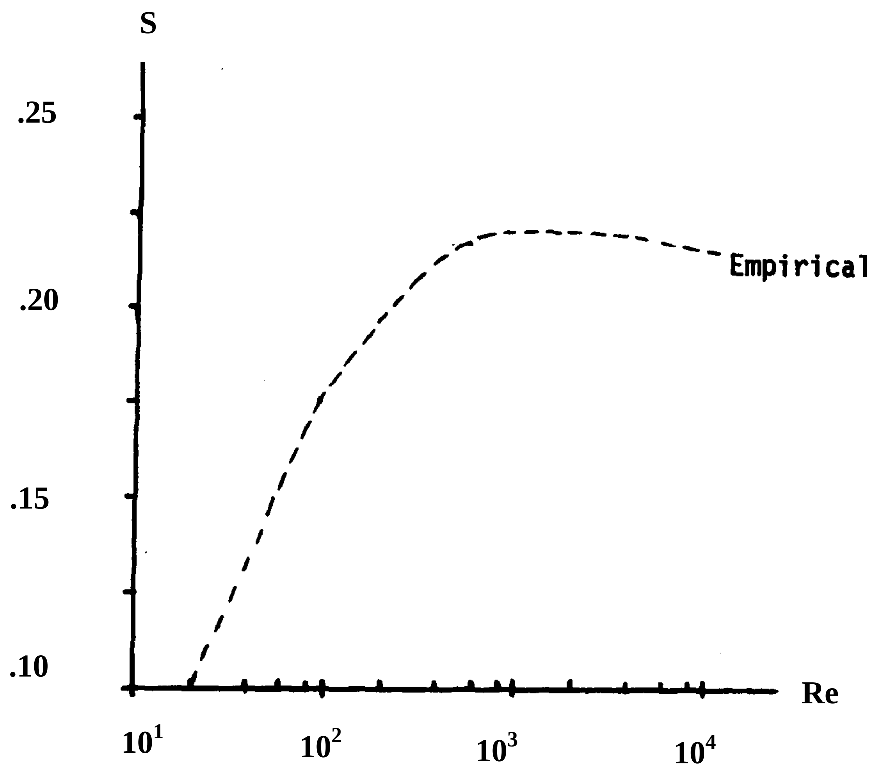


**Figure 12-2. Sketch of Strouhal Number vs. Reynolds Number for a Cylinder**

The mechanism of the periodic formation and shedding of vortices behind bluff bodies is not well understood although it is very important in structural problems, aerodynamic sound phenomena, aircraft performance, and geophysical problems, as well as problems related to atmospheric pollution. Because of their importance those phenomena are currently under investigation by fluid mechanicians.

The formation of the laminar von Karman vortex streets occurs in the range $40 < Re < 150$. Beyond $Re \cong 150$ transition to turbulence occurs at a location in the wake which depends on the Reynolds number. Generally, the point of transition moves towards the cylinder as the Reynolds number increases. The mechanism of transition from laminar to turbulent flow is another important problem related to the wake.

### 1.1.5 The Turbulent Wake

In a laminar flow the fluid particles move downstream in smooth and regular trajectories, without appreciable mixing between different layers of fluid. In a turbulent flow, on the other hand, an irregular and seemingly random motion is superimposed on the average downstream motion of the fluid. This *turbulence* involves a good deal of mixing and interchange of mass between different average streamlines. This mixing exchanges lumps of fluid between various streamlines. It is important to note that there is not simply a mutual exchange of mass, but an exchange of momentum between different streamlines. In the mixing process, slow-moving fluid is invigorated and speeded up by nearby fast-moving fluid, while the latter, in turn, is slowed down.

Turbulent flows are far more common than laminar flows, both in nature and in engineering devices. For example, the flow of water in rivers, the wakes extending from objects flying through the air and from ships on the sea, and the motion of the air in the atmosphere are practically always turbulent. A working knowledge of turbulent phenomena is absolutely essential in the practice of engineering. The energy of a body set in motion through an infinite volume of stationary fluid will eventually be dissipated as heat by viscous action within the fluid. For incompressible flow at high Reynolds number, the primary mechanism of dissipation is the turbulent wake. The energy of the body's motion is transferred to the kinetic energy of the turbulent fluctuations that define the wake. Viscous friction in turn causes these fluctuations to decay and their energy to be ultimately converted into heat.

Early investigators of this phenomenon found that energy "lost" from the free stream to the turbulent fluctuations was associated with a velocity deficit in the wake. From elementary consideration of the conservation of momentum it was clear that the magnitude of this deficit is a measure of the TOTAL drag acting on the body.

The fluid mechanics of the wake are thus of considerable practical importance. The properties of technical interest are the velocity distribution, the rate at which the wake grows in the downstream direction, and the mechanism by which scalar quantities such as heat and matter are spread outward into the undisturbed fluid.

The wake is a region of entrained fluid moving at nearly the velocity of the body. After the body has passed a given point, the turbulent region spreads and the fluid slows until viscosity damps all motion. In a wind tunnel the body is stationary and the fluid moves past the body. From a wind tunnel frame of reference, the wake profile is shown in Figure 3.

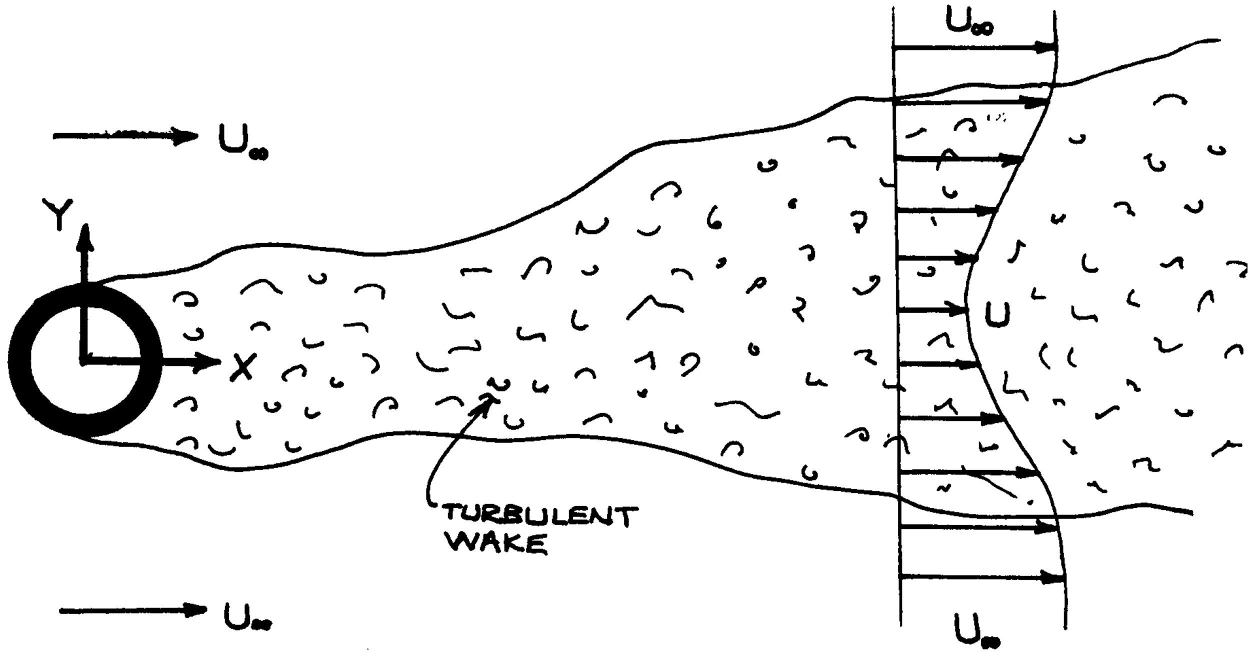


Figure 3. Sketch of a Turbulent Wake, in a Lab-Fixed Frame

The turbulent fluctuations that characterize the wake must be superimposed upon the mean profile shown. The boundary of the wake is determined by how far the velocity deficit and turbulent motion penetrate the surroundings. It is assumed the turbulent fluctuations decay as the mean velocity approaches the free stream velocity.

### 1.1.6 **The Intermittent Wake Boundary**

Observations have shown that turbulence does not taper off towards the boundaries of the wake. Rather, there is a sharp demarcation between turbulent and non-turbulent fluid. This surface shows up clearly in shadowgraphs of the turbulent wake, depicted in Figure 4.

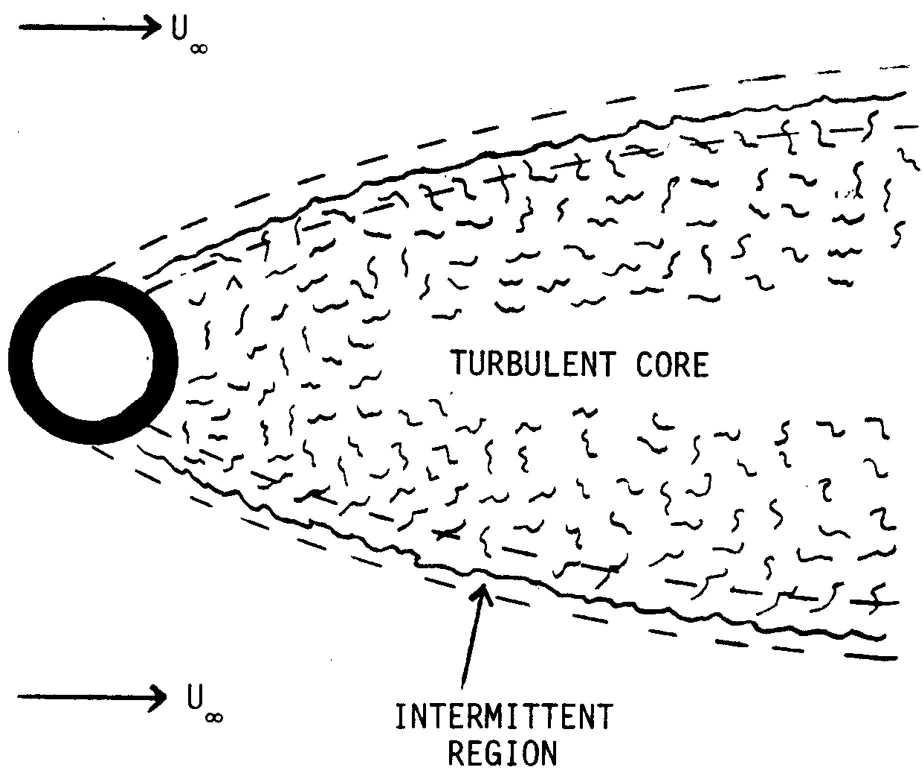


Figure 4. Schematic of a Wake Shadowgraph

A stationary probe placed near the wake will find itself swept over by successive regions of turbulent and non-turbulent fluid, giving an intermittent quality to the output signal.

The remarkable conclusion drawn from studies of this intermittent phenomenon is that a continuous range of states varying from fully turbulent to fully laminar does not ordinarily exist in nature. If both types of flow are present in a velocity field, they are distinct.

Actually, the phenomenon is a matter of common experience. If you have ever stood alongside a highway on which vehicles were moving at sufficient Reynolds number (say at 60 mph) and felt the wake pass over you, you have experienced the sharp boundary. The gust does not gradually rise to its full strength. Rather, at one instant you are standing in calm air and in the next the wind strikes you with its full force, surrounding you with the swirling gusts of the wake.

### 1.1.7 Relationship Between Drag and The Wake

The velocity profile (a plot of speed vs. a distance normal to the flow and the cylinder) of the wake at different distances downstream of the cylinder sometimes shows similarity, i.e., a similar pattern of streamlines varying in a manner relative to a geometric dimension. Figure 5 presents the nomenclature of the wake. The velocity deficit in the wake is:

$$u_1 = U_\infty - u, \tag{1}$$

where $U_\infty$ is the free stream velocity, and u is the velocity at some point in the wake. Note that $u \rightarrow U_\infty$ outside the wake.

As was mentioned earlier the total drag acting on the body depends on the velocity deficit. Applying the momentum theorem to a control volume that encloses the cylinder gives:

$$D = h\rho \int_{-\infty}^{+\infty} u(U_\infty - u)dy \qquad (2)$$

$$D = h\rho \int_{-\infty}^{+\infty} u_1 (U_\infty - u_1)dy \qquad (3)$$

where ρ is the fluid density, h is the height of the body, D is the drag force, and u is the velocity in the wake at point y. The detailed derivation can be found in Schlichting's text.

The drag on the cylinder can also be expressed as

$$D = \frac{1}{2}\rho A U_\infty^2 C_D \qquad (6)$$

where D is the drag, $C_D$ is the drag coefficient, ρ is the density, $U_\infty$ is the freestream velocity, and A is the frontal area of the body. For a cylinder, A = hd, where d is the diameter. The drag coefficient is somewhere around 1 (see prelab question 4).

For a wing, A is usually the chord times the span, as in Abbott and Von Doenhoff, *Theory of Wing Sections*, Dover, 1958, p. 3. The same reference gives a typical drag coefficient of 0.01 at zero angle of attack. For a wing of 10% thickness, this makes a drag coefficient based on the thickness of about 0.1.

One classical analysis shows that for self-similar wake sections,

$$\frac{u_1}{u_{1\,max}} = [1 - (y/b)^{3/2}]^2 . \qquad (7)$$

Figure 12-6 presents the curve of Equation 7. The similarity concept is displayed in this curve. In most cases, experiments show that the curve is independent of the distance downstream of the cylinder, provided that $x / (C_D\, d) > 50$.

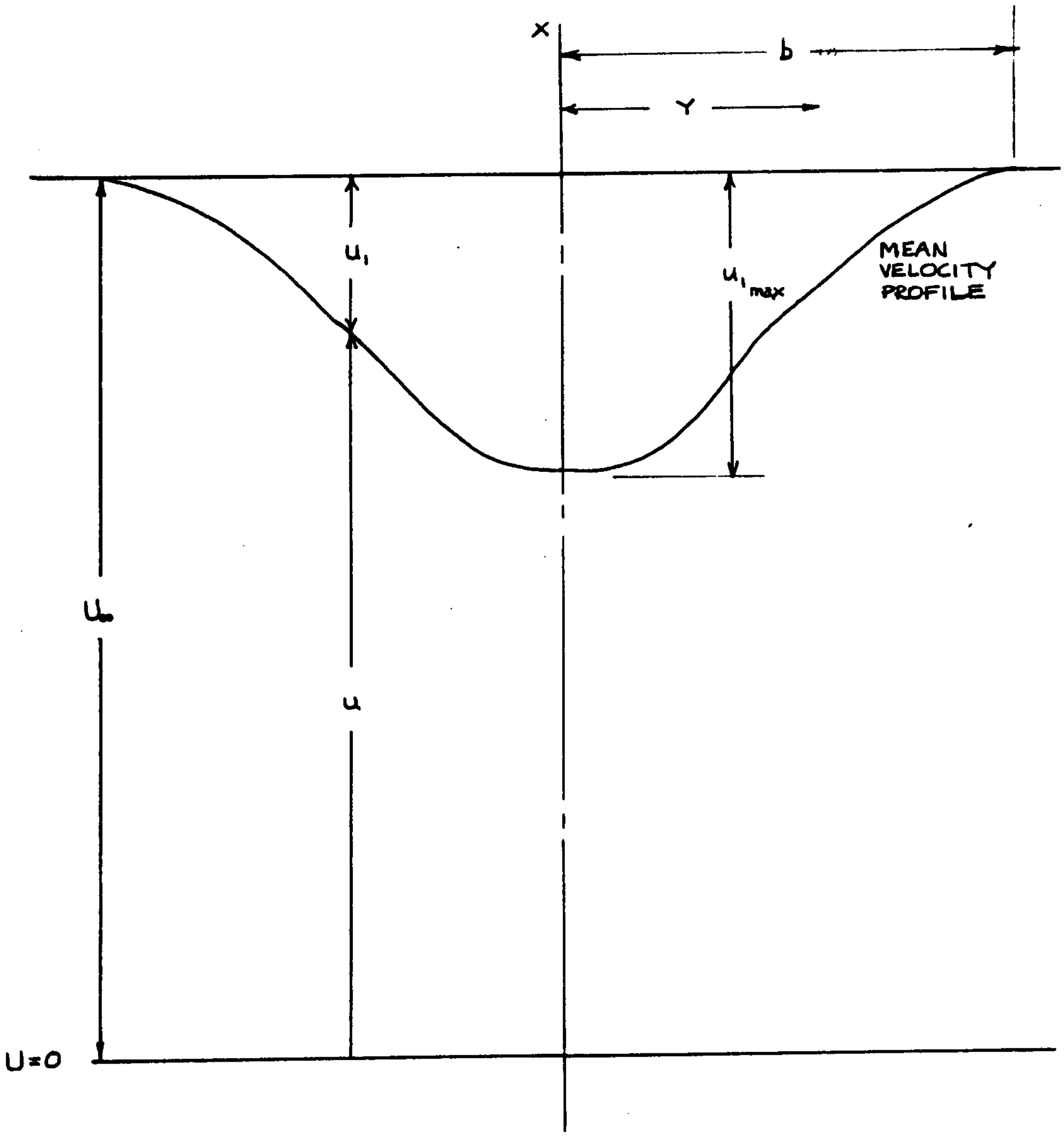


Figure 5.  Velocity Profile in a Wake

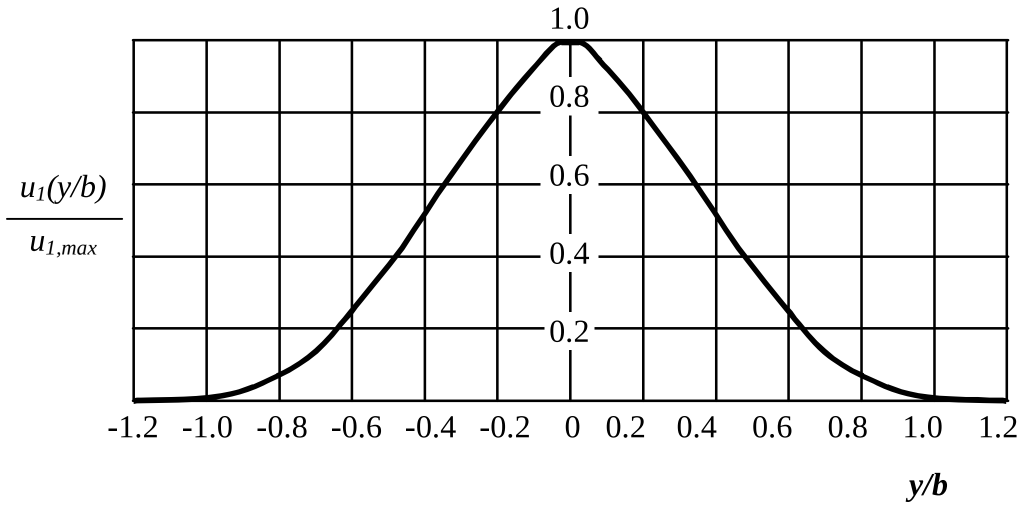


Figure 6. Classical Self-similarity in the Far Wake

### 1.1.8 Summary of the Wake Experiment

The cold resistance of a hot wire or film is found and the operating resistance is set. A calibration curve of the anemometer voltage vs. velocity is determined using a pitot-static tube. The velocity profile of the wake behind a body is then found using the anemometer.

The anemometer is driven across the wind tunnel behind the body by turning a crank. By sampling the flow at several points in the wake, the mean velocity profile can be generated. The data is for anemometer voltage vs. distance in the tunnel. This voltage can easily be converted to velocity by using the calibration curve obtained previously. The mean profile is then plotted. It is accompanied by profiles of the velocity fluctuations and by their power spectra.

The wake profile can be found for a circular cylinder, a NACA 0010 airfoil, and a NACA 2415 airfoil, and the results can be compared. The wake profile is to be examined at various downstream distances, achieved by placing the cylinder or airfoil at various positions upstream. In addition, the airfoil can be placed at plus or minus 3-degrees angle of attack, and the effect examined. A winglet is available for the NACA 2415 airfoil, for projects and advanced work. Besides the 1/2-inch diameter cylinder, there are also cylinders with 1/8-in. and 1/16-in. diameters, enabling experiments at lower Reynolds numbers. These smaller cylinders include a hook and basket that allows varying the tension in the cylinders to change the aeroelastic effects.

## 1.2 Lab Procedure

### 1.2.1 Prelaboratory Preparation

1. One accepted empirical curve-fit for variation with velocity of the voltage on a constant temperature hot film anemometer is King's law,

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

where U is the speed of the flow past the hot film, and V is the voltage on the hot film anemometer.

When the film is located at a fixed position in a nearly steady flow of mean voltage $\overline{V}$ and mean speed $\overline{U}$, small fluctuations in the mean voltage can be related to small fluctuations in the mean velocity, using a Taylor series approximation. Using this method, show that:

$$U' \simeq 4\left(A\overline{V}^2 + B\right)A\overline{V}V'$$

where $U' \equiv U - \overline{U}$, and $V' \equiv V - \overline{V}$.

*Hint*: This formula can be obtained from King's Law by direct substitution in less than a dozen lines. In King's Law, substitute the formulas giving the complete velocity and voltage in terms of their mean values and their fluctuations. Since the fluctuations are small, neglect products of the fluctuations compared to quantities linear in the fluctuations. Subtract off the equation for King's Law for the mean quantities (all the terms that don't involve the fluctuations). Use this equation to convert the rms fluctuating voltages to rms fluctuating velocities, by showing that

$$U'/\, U_{mean} = 4\, A\, V'\, V_{mean}/(A\, V_{mean}^2 + B).$$

This equation is valid only for small fluctuation levels, but is easily used to reduce your rms voltage data.

2. Another task that will have to be carried out during the lab is the numerical integration of data. Consider *n* data points $(x_i,y_i)$. There are many classical integration techniques for obtaining $I \equiv \int y dx$, when $h$ is a constant, where $x_{i+1} - x_i = h$. However, in experimental work it is often best not to be limited to a constant *h*. By drawing a graph and considering the area under a trapezoid, show that

$$\int_a^b y dx \simeq \sum_{i=1}^{n-1} \frac{1}{2}(x_{i+1} - x_i)(y_{i+1} + y_i)$$

where $x_1 = a$ and $x_n = b$. This formula is much superior to the rectangle formula - why? The formula becomes exact as $n \rightarrow \infty$; why? Prepare yourself to rapidly use this formula to integrate your experimental data - you need only use about 10 points during the experiment to provide a rough estimate of the integral. Further information about numerical integration can be found in an introductory text. For example, the trapezoidal method for constant *h* is treated in *Calculus and Analytic Geometry*, 4th edition, G. B. Thomas, Addison Wesley, 1969, on page 178-180.

3. Consider a signal *u(t)* which varies about some mean value

$$\overline{u} = \frac{1}{T}\int_0^T u(t)dt,$$

where T is long. The amplitude of the fluctuation $u' \equiv u - \overline{u}$ can be characterized using its rms amplitude

$$u'_{rms} \equiv \sqrt{\frac{1}{T}\int_0^T (u')^2 dt}$$

Compute $\overline{u}$ *and* $u'_{rms}$ for an ideal sine wave signal,

$$u(t) = A + B\sin\omega t\,.$$

Why do we use $u'_{rms}$ and not some other quantity to characterize the fluctuations?

4. Empirical cylinder wake drag data can be curve fit using

$$C_d \simeq 1 + 10.0R^{-2/3}$$

where $C_d = D/(0.5\rho U^2 d)$ and $R = U\,d/\nu$.  Here d is the diameter of the cylinder, D is the drag on the cylinder per unit depth of cylinder, $\rho$ is the fluid density, and U is the speed of the uniform flow past the cylinder (see White, *Viscous Fluid Flow*, 2nd edition, p. 183).  This formula is fairly accurate for $1 < R < 2 \times 10^5$.  Plot this curve for Reynolds numbers between 50 and 10000, so that you can later compare your experimental data against it.

### 1.2.2 Introduction

The mean velocity profile in the wake behind a test body placed in the wind tunnel will be examined. From these mean velocity profiles, the drag on the test body can be determined.  Measurements of the unsteady turbulent velocities will also be made.  A hot film or wire will be used to make the measurements; this is very similar to the hot film used in the AAE333L Basic Flow Measurements lab, except that it is more fragile and has a higher frequency response.  See Figure 7 for a schematic of the apparatus.

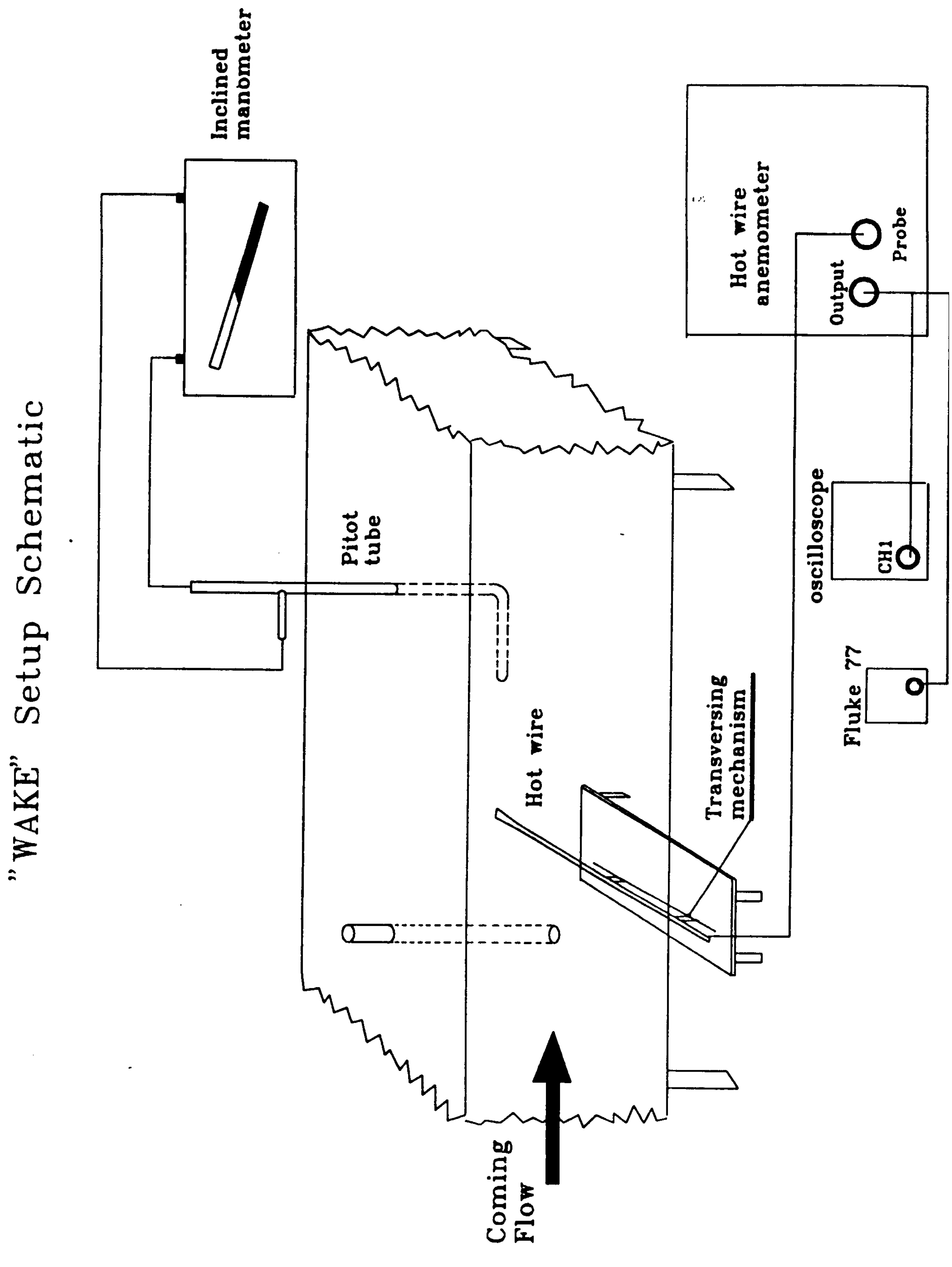


**Figure 7  Wake Apparatus Schematic**

A test body is placed in the wind tunnel. This test body will create a wake downstream when the tunnel is running. A constant-temperature anemometer is used to determine the velocity downstream (in the wake) of the test body. The hot-film probe will start in the freestream flow on one side of the wake, pass through the wake of the test body, then back into the freestream flow on the other side of the wake. The hot film will be traversed using the precision Unislide traverse, which can be read to give the position of the hot film. The mean wake velocity can be obtained from the mean voltage on the hot film. If at least ten points per wake profile are obtained, an estimate of the drag can easily be obtained.

The experiment consists of the following parts:

- Part A: Starting and stopping, setting velocity and measuring pressures in the Wake Wind Tunnel.
- Part B: Traversing Mechanism.
- Part C: Anemometer Setup.
- Part D: Calibrating probe.
- Part E: Take data: Wake profile. Descriptions of unsteady flow by studying the hot film signal using an oscilloscope. Measurements of the RMS velocity fluctuations and power spectra. Frequencies of the vortex shedding.
- Part F: Turning off equipment.

### 1.2.3 Data to be Acquired

1. Wake profile for a cylinder and airfoil. Place the cylinder in several of the holes available upstream of the probe. Try the airfoil in both of the upstream positions that are available. Try the airfoil at angle of attack, also.
2. Measurements of the unsteady component of velocity in the wake and freestream. Frequencies of the vortex shedding. Spectra.

### 1.2.4 Part A: Starting and Stopping, Setting Velocity and Measuring Pressures in the Wake Wind Tunnel

1. DO NOT turn on the wind tunnel until instructed. The wind tunnel should not be turned on in Part A. Part A explains how to start and stop the tunnel, set the tunnel air velocity and measure pressures in the wind tunnel.

2. The Wake Wind Tunnel consists of:

    - An contracting inlet which is assumed isentropic.
    - A plexiglas, constant cross-section test section in which the experiment is performed.

- A diffuser and an electric motor driven blower.

The fans draw the air through the inlet, down the test section and exhaust the air through the top of the blower.

3. The Wake Wind Tunnel can be started by pushing the green START button and stopped by pushing the red STOP button. These buttons are located on the fence near the blower. DO NOT start the tunnel.

4. The speed of the wind tunnel can be adjusted by moving the sliding panel SPEED CONTROL located on top of the blower.

5. A pitot-static tube measures the freestream dynamic pressure in the tunnel. This freestream Dynamic Pressure relates to the freestream velocity in the wind tunnel.

6. The pitot-static tube is connected to a slant-tube manometer, similar to the ones used in earlier labs. The manometer gives the freestream value of the dynamic pressure.

7. After adjusting the speed in the tunnel, you should wait about 20-30 seconds to allow the manometer to stabilize.

### 1.2.5 Part B: Traversing mechanism

**1.** The TRAVERSING MECHANISM guides a steel shaft across the wind tunnel. The HOT-FILM ANEMOMETER PROBE (hereafter referred to as the PROBE) is on the end of the steel shaft. Using the handcrank on the traverse, traverse the probe back and forth across the tunnel to become familiar with the operation of the traversing mechanism. **The traversing mechanism has stops to prevent the probe from hitting the walls of the tunnel. DO NOT FORCE the traverse up against the stops ! BE GENTLE WITH THE TRAVERSE !**

2. Retract the PROBE as far as possible toward the near side of the tunnel. Note that 40 turns of the crank correspond to one inch of movement, so that the dial on the crank provides 0.001 inch marking accuracy with which to interpolate between the scale markings on the side of the traverse. Estimate the reading on the scale when the probe is immediately behind the cylinder.

### 1.2.6 Part C: Anemometer Setup

1. The "Intelligent Flow Analyzer" (IFA) and the PROBE will be used to measure the speed in the wind tunnel. The IFA will keep the probe at a constant temperature, hence the voltage supplied to the probe is proportional to the speed.

2. Turn ON the IFA. This device has flush mounted buttons, after each one is pushed a small tone will be heard. The IFA should be on STANDBY (red light next to RUN is OFF).

3. Check the switches and connections on the back of the IFA: the hot film should be hooked to the `STD' connector, averaging should be OFF, the signal conditioner on INTernal, coupling on DC, and the sensor switch set to `film' (if using a film), or `wire' if using a wire.

4. The probe cold resistance must be known, to set the anemometer overheat; it should be measured using the low-current HP3478A. The value may also be posted on the anemometer. Record this cold resistance.

5. To find the operating resistance, multiply your cold resistance by an overheat ratio of 1.25 to 1.5. Lower values provide a conservatively low operating temperature that prolongs the life of the films.

6. 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.

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

8. PRESS: RUN/STANDBY (Be sure red light next to RUN is on.) This sends current to the hot film. The anemometer is now running.

9. Check the anemometer signal on the oscilloscope to make sure it is not oscillating. If you get a signal with very high frequency oscillations, with a period of roughly 1 microsecond, the anemometer has become an oscillator, due to small amounts of stray reactance, and adjustments or repairs need to be made. What do the turbulent fluctuations look like?

### 1.2.7 Part D: Calibrating the Hot-Film or Hot-Wire Probe

1. Level and set the initial REFERENCE READINGS for the manometer.

2. Connect the multimeter to the output of the anemometer, to read the mean voltage on the anemometer.

3. Turn on oscilloscope. This will allow the oscilloscope to warm up before being used. Connect the oscilloscope to the anemometer output, in parallel with the multimeter. The oscilloscope output should be monitored during the calibration to make sure no unusual circuit oscillations develop during the calibration.

4. Set the anemometer to Run.

5. Check to make sure the tunnel is empty (the cylinder is out). If the cylinder is in the tunnel, remove it.

6. Turn on the tunnel.

7. Read this entire step before continuing: These steps continue the anemometer calibration:

   a) Set a new value to the tunnel speed, by moving the panel on top of the blower.

   b) After letting the manometer stabilize, record the Dynamic Pressure. Then, record the average voltage on the anemometer output, by reading the voltage on the voltmeter. The voltage fluctuates a little, even in the freestream. Obtain the mean voltage using the averaging feature of the HP34401A multimeter (Appendix B.)

   c) Repeat the above steps for other values of dynamic pressure between 0.0 and the maximum value given you by the T.A., perhaps as much as 0.4 inches of water. (A total of seven or more.) Make a neat table of the voltage and pressure readings; leave room for several more columns of data. This data will be used to calibrate the anemometer. Do not use data with zero flow - why?

8. Turn off the tunnel.

9. Record the FINAL REFERENCE READINGS for the manometer.

10. 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.

11. 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.

12. Determine the best fit constants in the equation $\sqrt{U} = AV^2 + B$ using a least squares fit to the data.

13. Now you have a procedure for obtaining U from V, which you will use in the following part of the lab. Repeat the calibration after running some experiments, to determine how much drift has occurred.

### 1.2.8 Part E: Wake Profiles

1. Record an initial reference reading for the manometer.
2. Turn on the wind tunnel and set the tunnel speed to some value of your choice.
3. Using the traverse, set the hot-film probe to one side of the wake. The edge of the wake can be identified by noting where the hot film output voltage no longer varies with the position. It should be several cylinder diameters from the center of the tunnel. This initial location for recording data is essentially in the freestream of the tunnel.
4. Record the dynamic pressure reading on the manometer.
5. Repeat the following procedure for each data point to be taken:

- Traverse the hot film somewhat further across the wake of the cylinder. When the hot film output has changed significantly, stop turning the traverse crank, and record the traverse position.
- Record the output voltage of the anemometer. Using your calibration curve-fit, translate this voltage to velocity. Plot this velocity against the hot-film position.
- Record the rms fluctuations of the anemometer voltage. This can be done using the "measure" function on the oscilloscope. In the measure menu, measure "standard voltage parameters" -- the "standard deviation" is equal to the rms voltage, within a factor of N/(N+1), where N is the number of points averaged.
- Record the frequency of any peaks in the power spectrum of the voltage.

6. Take at least 10 wake velocity points as you traverse the wake of the cylinder. At each point, observe the unsteady velocity in the wake, and measure the root mean square fluctuation voltage. Note that the anemometer voltage fluctuations in the freestream should not be more than 10-15 millivolts peak-peak; if the anemometer does not seem to be working properly, consult with your TA. Convert your observed voltage to an estimated RMS fluctuation velocity using the formula for small fluctuations derived in the prelab work. Is the freestream turbulence level in this tunnel high or low? A turbulence level of 0.3% of the freestream velocity is mediocre.
7. Record a final manometer reading and temperature, at the tunnel velocity chosen.
8. Turn OFF the Wind Tunnel.
9. Record FINAL REFERENCE READINGS for the manometer head and the hot film voltage. Have the final reference readings changed much from the original readings? What does this say about the accuracy of your manometer data?
10. Repeat the measurement for some conditions. How good is the repeatability?
11. Repeat this section for the airfoil model. Since the airfoil drag coefficient is so much smaller, how will the wake compare? Should you plan to take the airfoil data in a different set of locations?
12. As time allows, repeat this part for the airfoil at angle of attack and other upstream locations, for the cylinder at other upstream locations, and for other tunnel speeds.

### 1.2.9 Part F: Turning off the Equipment

- Switch the anemometer to STANDBY.
- Turn off the Tunnel and replace the manometer cover.
- Turn off the anemometer.
- Turn off the Oscilloscope and the voltmeter.

## 1.3 Analysis

Consider the following issues when writing your report:

a) Integrate the velocity data from the cylinder and airfoil wake profiles, using the trapezoid rule for unequal spacing discussed in the prelab.
b) Using results of #1 above, compute the drag coefficient and Reynolds number of the cylinder. Compare your result to the accepted empirical curve. Discuss the difference between your result and the accepted value, in terms of the errors present in the experiment.
c) Compare the data for the airfoil model(s) to theory and to the cylinder-wake data. You may wish to consult Abbott and Von Doenhoff, "Theory of Wing Sections", Dover, 1959, which contains empirical data.
d) Plot the rms velocity fluctuations versus position, for both models, on the same graphs that show the mean velocity. Where do you see large and small rms values?
e) If you were able to measure any peaks in the power spectrum of the hot-film signal, compute the Strouhal numbers from these peaks. Do these Strouhal numbers agree with previous empirical relations? How does the vortex shedding vary with Reynolds number? Were you able to test the 1/8 or 1/16-in. cylinders, in addition to the 1/2-in. diam. cylinder? How was the flow different at the lower Reynolds numbers?
f) Determine the effect of angle of attack on the airfoil wake.
g) Determine the effect of upstream location on the airfoil and cylinder wakes.
h) Determine the effect of tunnel velocity on the wake measurements.
i) Discuss the power spectral data for various locations in the wakes under different conditions.
j) Describe the sources of error in the experiment.