AC 2007-2821: THE WIND TUNNEL AS A PRACTICAL TOOL FOR THE DEMONSTRATION OF ENGINEERING FLUID MECHANICS AND PRINCIPLES OF AERODYNAMIC DESIGN

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The Wind Tunnel as a Practical Tool for the Demonstration of Engineering Fluid Mechanics and Principles of Aerodynamic Design

Abstract

Laboratories which make use of wind tunnel experimentation play an important role in many undergraduate courses in the fluid and thermal sciences area, including those associated with aerodynamics and fluid mechanics courses. Measurements of the lift, drag and pitching moment behavior of airfoils as a function of angle of attack are a common occurrence in such labs. The importance of reinforcing theoretical aerodynamic concepts is clear, but the challenge is to provide meaningful experiments that demonstrate the desired effects without either introducing numerous extraneous phenomena, or overly complicating the experimental procedure.

This paper presents the authors experience with an Aerolab educational wind tunnel test facility as part of course-related work in both junior-level Fluid Mechanics (ME571) and senior-level Aerodynamics (ME628) courses. The simple addition of several special-purpose pressure taps, to complement existing built-in pressure taps normally associated with the standard test section region, provide the means to map the axial pressure distribution within the entire wind tunnel. This allows direct identification of the location(s) of significant mechanical energy losses, through comparison with ideal inviscid stream tube analysis associated with fluid mechanics principles. In particular, the losses associated with the diffuser section become very apparent, in contrast with the inlet convergent section. Pressure recovery in the diffuser section is modeled in a very simple manner and compared directly with wind tunnel measurements. Fan power requirements associated with wind tunnel design are also included as part of the experimentation. The connection between diffuser loss behavior and boundary layer separation phenomena associated with flow over a wing is also brought out in these experiments.

Introduction

Wind tunnel testing is a common component to an introductory engineering aerodynamics course. Experimental measurements of lift, drag, pitching moment, and pressure distribution (or pressure coefficient) have long been a significant part of such introductory courses, and the analysis of these physical characteristics is a very important step toward the introduction of principles of aerodynamic design—in particular airplane design. In addition to the more common use of the wind tunnel as a tool for investigation of the aerodynamics of sting-mounted test models, however, the wind tunnel itself provides a means to demonstrate significant principles of fluid mechanics and the application of these principles to aerodynamic design. Properly instrumented, it can provide an excellent demonstration of both ideal inviscid fluid flow behavior, as well as the affect of mechanical energy losses on wind tunnel design.

Typically commercially-available wind tunnels come equipped with standard pressure taps for sensing the test section pressure level. This test section pressure, relative to the ambient atmospheric pressure (i.e., the test section gage pressure), is also commonly used to determine the test section airspeed, which can then be directly displayed on the instrument panel associated with the wind tunnel. For more accurate local airspeed measurements, a small Pitot probe can be inserted and positioned anywhere desired within the test section. Both the Pitot probe and the airspeed indicator just mentioned rely on Bernoulli's fluid mechanics principle to relate pressure to flow. Closely associated with the application of this principle is the concept of a so-called "stream tube" which defines a region bounded by adjacent streamlines in the flow. Furthermore, the application of the Bernoulli principle involves the assumption of inviscid (frictionless) flow, and hence negligible loss of mechanical energy as the flow passes through a given stream tube.

The wind tunnel itself can be thought of as an example of a stream tube. This simple concept is routinely used to deduce the average airspeed in the test section region by the application of the Bernoulli principle to the flow confined within a stream tube connecting the inlet ambient (approximately stagnant) atmospheric conditions to those just downstream of the inlet converging region of the test section. This forms the basis of the wind tunnel airspeed indicator operation. The objective of this paper is to illustrate that the entire wind tunnel can be used to further demonstrate these principles, and to give this authors experience with simple inexpensive modifications to an existing wind tunnel facility to achieve this end. The modifications involve the addition of inexpensive pressure taps to give a much more detailed picture of the distribution of pressure and hence also mechanical energy losses in the stream tube comprising the wind tunnel region. This readily shows that the major source of these losses is associated with the diverging section, in obvious contrast to the converging inlet section. Identification of these losses represents an important component to be considered in the design of the wind tunnel itself, as they are directly related to the power requirements to drive the flow. Introducing students to the strengths as well as the limitations of analytical tools such as Beronoulli's equation, is extremely important to a meaningful experience in both aerodynamics and fluid mechanics laboratory settings.

Wind Tunnel Facility

Figure 1 shows the existing Educational Wind Tunnel associated with the current development. A photograph of the overall facility is shown in Figure 1(a), and a view of the upper surface of the wind tunnel and new pressure tap locations is shown in Figure 1(b). While relatively

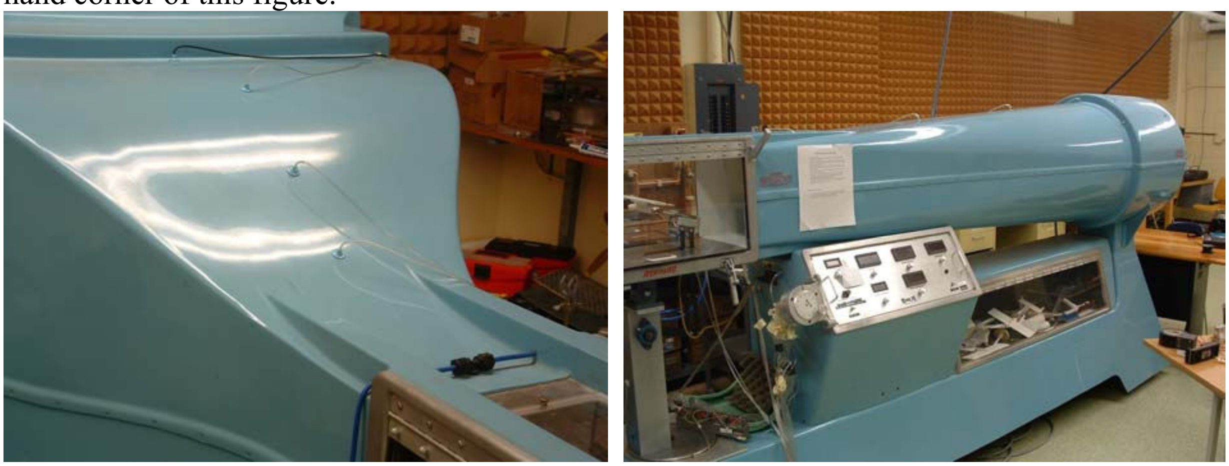
(a) Wind Tunnel **(b) Pressure Taps**

Figure 1: Educational Wind Tunnel Facility

inexpensive in comparison to some wind tunnels, this facility has been demonstrated to be capable investigating a wide variety of phenomena of interest to fluid mechanics and aerodynamic courses [1-3]. The wind tunnel has a test section measuring 12 in x 12 in x 24 in (305mm x 305mm x 610mm), and has a maximum air speed of approximately 140 mph (63 m/s). It is instrumented with an electronic strain-gage based balance for measurements of normal force, axial force, pitching moment, and pressure distribution as a function of air speed and angle of attack. Manual measurements are accessible from a front panel digital display, and electronic data acquisition is also available for remote access and real-time measurements.

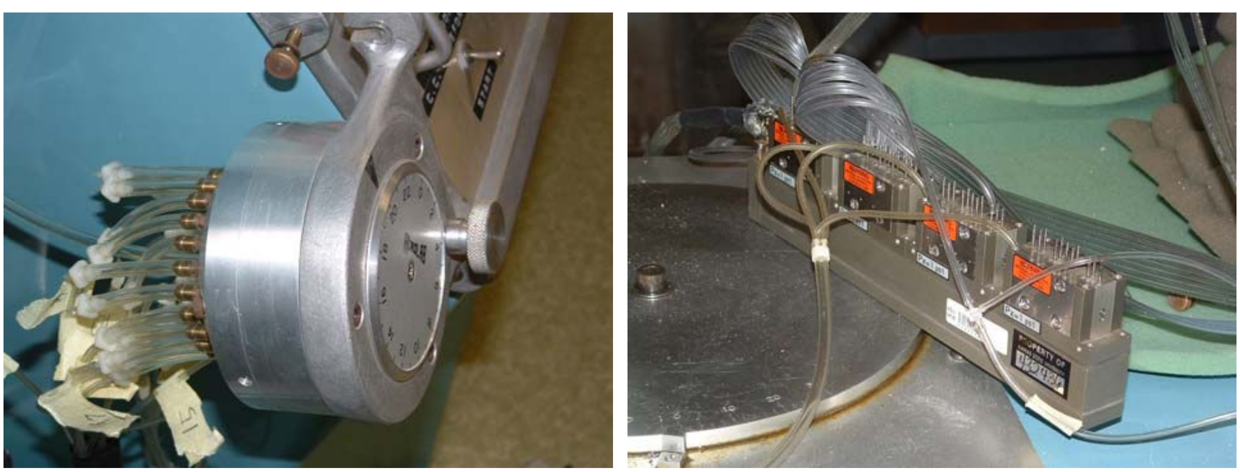
Pressure Measurement

Figure 2 shows the location of pressure taps on the wind tunnel facility. Figure 2(a) shows a photograph of the inlet region (converging section) just upstream of the test section area. The original pressure ring used by the wind tunnel for airspeed indication is shown in the lower right-hand corner of this figure.



(a) Inlet Pressure Tap Locations **(b) Downstream Pressure Tap Locations**

Figure 2: Wind Tunnel Pressure Taps



(a) Manual Multi-port Pressure Valve **(b) Electronic Pressure Scanner**

Figure 3: Manual and Electronic Pressure Measurement

Pressure taps that were subsequently added to provide more detailed pressure distribution information are shown in both Figures 2(a) and 2(b), and are located on the top surface of the wind tunnel.

Both manual as well as electronic pressure sensing is available on this facility. Figure 3(a) shows a photograph of the manual valve used to select individual pressure tap lines on the existing facility. An electronic pressure scanning unit containing 32 individual electronic pressure sensors is shown in Figure 3(b). This latter unit can be use to provide real-time visualization of the pressure distribution in the wind tunnel, in much the same manner as it has been used to visualize the pressure distribution associated with airfoils and wings [3].

(a) Parts Break-down for Pressure Tap **(b) Assembled and Mounted Tap**

Figure 4: Pressure Tap Construction

The construction of the additional pressure taps is illustrated in Figure 4. Each of the additional taps was formed from an inexpensive plastic tubing adapter, a steel hex nut, with a flat washer as a base. The individual parts were bonded with epoxy and spray-painted to match the color of the wind tunnel housing (light blue). A matching color caulking compound was used to bond the tap to the wind tunnel wall (top surface).

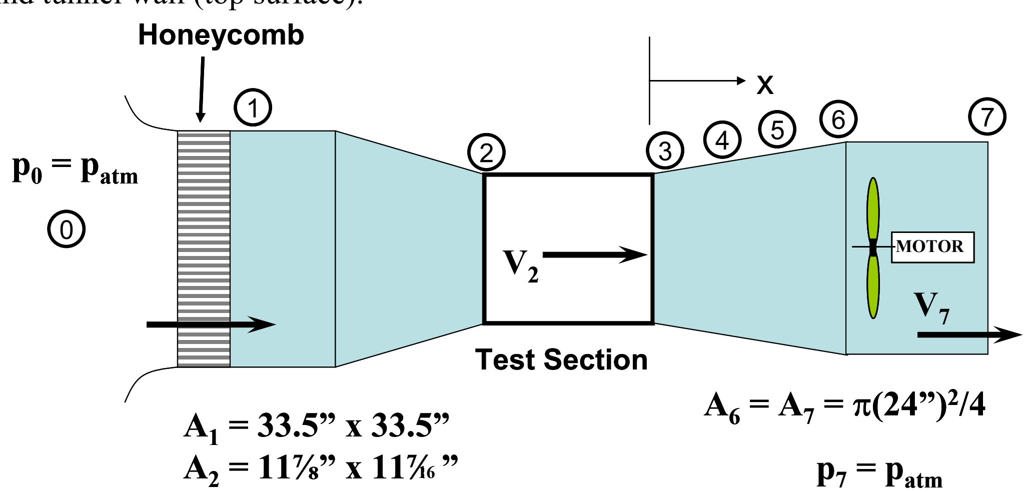


Figure 5: Simplified Schematic of Wind Tunnel

Prior to mounting of each tap, a small vent bore hole (#60 drill) was made through the wall of the wind tunnel fiber glass housing to facilitate sensing of the static pressure on the inside wall of the tunnel.

The distribution of pressure tap locations is shown schematically in Figure 5, which gives a simplified diagram of the wind tunnel. More pressure taps than shown in this diagram have subsequently been added to the inlet converging section of the wind tunnel, however, these are not included in the current measurements. The inlet pressure ring, which was part of the original wind tunnel, is represented by pressure tap #2 in this diagram. The approximate dimensions of selected sections of the wind tunnel cross-section are also shown in this figure.

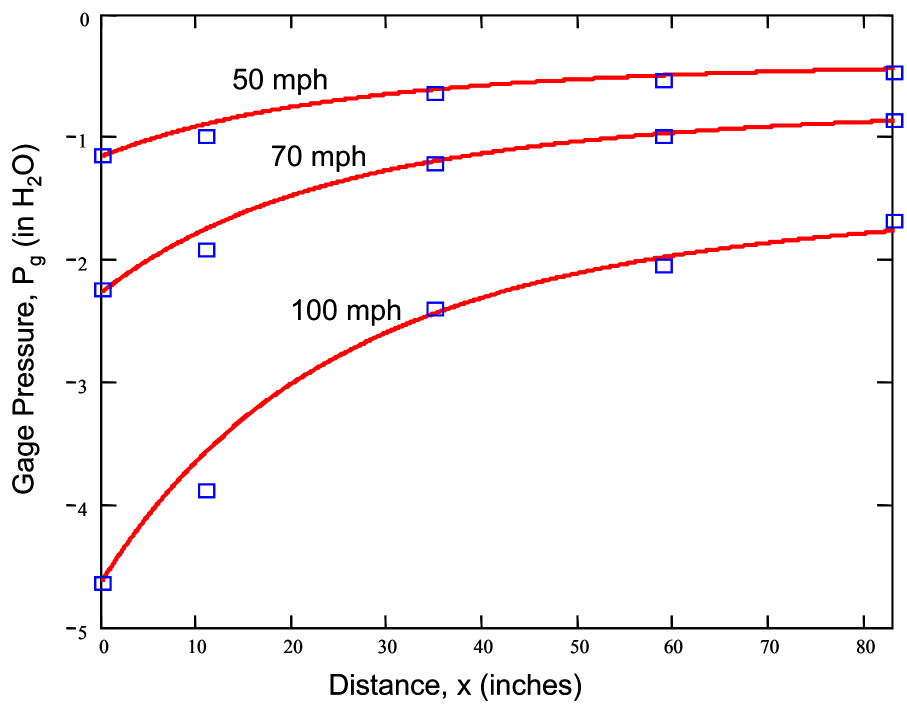


Figure 6: Measured and Predicted Wind Tunnel Pressure Distribution

Figure 6 shows a plot of the pressure distribution in the diverging section (diffuser) of the wind tunnel. The squares represent the measured gage pressures at the above prescribed pressure tap locations for three different air speed settings ranging from 50 to 100 mph. Nominal experimental uncertainties in pressure measurement range from about ± 0.03 to ± 0.10 in H_2O for this range of airspeeds. This plot illustrates the pressure recovery (diffuser) section of the wind tunnel, which is just upstream of the blower which drives the flow. This diffuser section reduces the pressure head that the blower must overcome, and hence significantly reduces the power required to operate the wind tunnel. This is one of the important design aspects brought out in this type of experiment. In addition to the measured pressure distribution, a simple model based on constant pressure recovery efficiency [4-5] is also shown in Figure 6. The recovery efficiency gives rise to a very simple model for head loss in the diffuser section as follows:

$$h_L = K(x)\frac{V_2^2}{2g} \qquad (1)$$

where K(x) is a loss coefficient for losses up to any arbitrary position x along the diffuser and is defined below as follows in terms of the diffuser efficiency, η.

$$K(x) = (1-\eta)\left[1-\left(\frac{A_2}{A(x)}\right)^2\right] \quad (2)$$

A simple approximate fit to the cross-sectional area of the wind tunnel, A(x), was used to generate the smooth predicted result above, with an approximately constant diffuser efficiency of about 70%. From calculations of the airspeed and pressure in the test section using Bernoulli's equation without losses, it becomes clear to the students that the head losses in the inlet converging section are minimal, and largely result from losses in the flow straightening section upstream of the test section. The major source of wind tunnel head losses come from the diffuser section, which is clear if the predicted pressure distribution (without losses) is compared to the results presented in Figure 6. Physically the presence of these losses can be partially explained in relation to the effects of boundary layer separation in the diffuser section, similar to that which occurs on the upper surface of a wing. This is one of the purposes of this lab exercise. It has been a very useful addition to theoretical concepts and complements both undergraduate fluid mechanics theory, as well as introductory aerodynamics theory quite well.

In addition to pressure distribution, estimates of the power requirements are also important to bring out in this type of experiment. Figure 7 shows the power requirements as a function of airspeed in the test section. The solid line is predicted from a simple stream tube energy analysis including the effects of head loss described above.

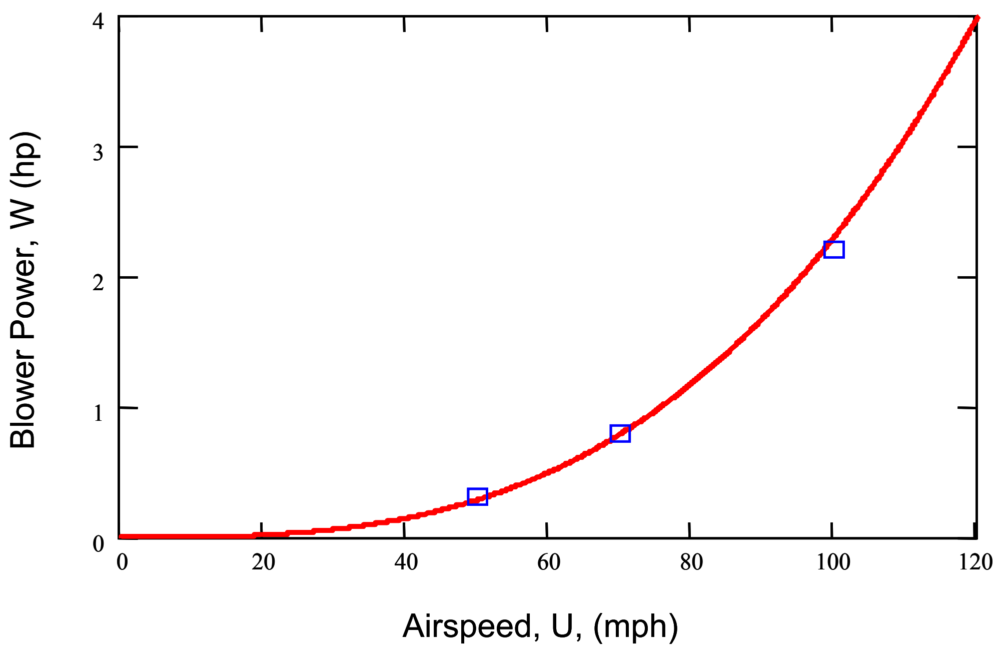


Figure 7: Wind Tunnel Blower Power Requirements

The data points are calculated power requirements based on the measured pressure drop across the blower. This corresponds to the power delivered to the flow by the combined motor/blower system. Instrumentation is not currently available for direct measurement of the power input to the blower; however, such an addition is planned for future upgrades of the wind tunnel setup. This addition would then allow measurement of overall energy conversion efficiency. However, the power levels shown in Figure 7 are very reasonable considering the fact that the wind tunnel is designed for a maximum test section airspeed of about 150 mph using a 10 hp blower. Extrapolation of the above plot clearly indicates that these maximum power requirements are in the proper range.

Summary and Conclusions

This paper presents the authors recent experience with a simple modification to an existing Aerolab educational wind tunnel test facility. This facility is used for experimentation to complement theoretical work associated with both junior-level Fluid Mechanics (ME571) and senior-level Aerodynamics (ME628) courses. An inexpensive method of constructing simple and effective special-purpose pressure taps is presented, which could be incorporated into virtually any wind tunnel facility. These taps significantly complement existing built-in pressure taps normally associated with the standard test section region, and are shown to provide the means to map the axial pressure distribution within the entire wind tunnel. They also provide a means of assessing the validity of the Bernoulli principle and provide further reinforcement of the stream tube concept in relation to the wind tunnel flow.

Measurements of the pressure distribution confirm the presence of significant mechanical energy losses, through comparison with ideal inviscid stream tube analysis associated with fluid mechanics principles. In particular, the losses associated with the diffuser section become very apparent, in contrast with the inlet convergent section. Pressure recovery in the diffuser section is modeled in a very simple manner and compared directly with wind tunnel measurements. Fan power requirements associated with wind tunnel design are also included as part of the experimentation and are shown to be very reasonable in comparison to the existing blower power. The connection between diffuser loss behavior and boundary layer separation phenomena associated with flow over a wing is also brought out in these experiments. Future additions planned include the acquisition of direct blower power measurement. In addition, smoke visualization of the flow characteristics within the diffuser section would provide even more reinforcement of the mechanisms associated with the existence of significant losses in this section, and how they are important to practical wind tunnel design.

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