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Using Inexpensive Modern Equipment in Teaching Turbulence to Undergraduate Engineering Students

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Abstract

This paper summarizes the development of four laboratory experiments designed to enhance learning of turbulence theory by undergraduate engineering students. The concepts taught by these experiments included boundary-layer structure, flow separation, vortex shedding, surface pressure distributions, Reynolds stress, and statistical description of turbulent motion. The required equipment included an Acoustic Doppler Velocimeter and a low-range transducer for velocity and pressure measurements in water flows, a PC-based data acquisition system, and a water channel. Because the instruments were relatively inexpensive and the experimental procedures were simple and practical, these experiments can be readily adapted at other institutions. Initial responses from students were extremely positive.

I. Introduction

Most fluid flows occurring in engineering applications are turbulent. A typical example is the local scour produced by turbulent flow at bridges. Another example is the transport and dispersion of contaminants in rivers, lakes, estuaries and the coastal ocean. A good physical understanding of turbulence is important for solving many engineering problems dealing with fluids in motion. However, teaching turbulence to undergraduate students is a challenge because turbulent flow is complex and much of the information about turbulence has been gained from laboratory studies. Lectures alone are not very effective in learning the theory of turbulence. Physical understanding of turbulence should include visualization of turbulence phenomena as well as laboratory experimentation that provides hand-on experience. In the classroom, students may observe turbulent flows through a series of films produced by the National Committee for Fluid Mechanics Film (NCFMF)[2]. In the laboratory, the Reynolds's experiment is often performed as an introduction to laminar or turbulent flow. This experiment involves observing the mixing of a dye filament across the flow in a tube and the increase in pressure drop along the tube as the flow becomes turbulent. Other experiments in turbulence will require more sophisticated equipment, and thus are not always performed in undergraduate fluid mechanics laboratories.

The basic concepts of turbulent flows that are covered in a typical undergraduate fluid mechanics course include transition from laminar to turbulent flow, boundary-layer structure, flow separation, vortex shedding, and surface pressure distributions in flow over immersed bodies. More advanced topics may include Reynolds stress, self-similarity, and statistical description of turbulent motion. Because velocity and pressure are of primary interest in a fluid flow, learning of turbulence concepts will be greatly improved if students can measure these quantities in the observed flow. A few years ago, Dantec Measurement Technology developed a laser-Doppler anemometer (LDA)-based fluid mechanics laboratory station. This apparatus included a one-component LDA with one frequency tracker and shifter, data acquisition board, software, and a water tunnel with accessories for simulating flow through a pipe, a turbulent jet, and flow around an airfoil and a circular cylinder. The basic system cost about $20,000, and it could be used to illustrate such concepts as velocity distributions in laminar and turbulent pipe flows, jets, wakes, separated flow, and vortex shedding.

The focus of this paper is to use relatively inexpensive modern equipment to develop our own laboratory experiments for enhancing undergraduate learning of basic turbulence concepts. The project equipment includes an Acoustic Doppler Velocimeter (ADV) for measuring velocity in water flows, a differential pressure transducer for measuring pressure, and a data acquisition system and personal computer for data collection and display. The project also requires an open-channel flume that is standard equipment in many hydraulics laboratories. Four new experiments (velocity profile in open-channel flow, turbulent shear stress, flow behind a pier, and pressure distribution on a circular cylinder) were developed. Students from two undergraduate classes (CEE 331 Fluid Mechanics Laboratory and CEE 493 Environmental Fluid Mechanics) conducted these experiments. Because the experimental setup and procedure were simple, these experiments may be readily adapted at other institutions. Furthermore, the instruments are flexible so new experiments can be developed when course materials are changed. The latter is particularly important in small universities and colleges that may not have a lot of resources for purchasing new equipment. In this paper, we summarize the experiments developed and discuss the impact of the project on students.

II. Experimental Equipment

Since turbulence is a random, fluctuating and three-dimensional flow, it is necessary that the instruments for velocity and pressure measurements have fast frequency responses. It is also desirable that the instrument for velocity measurements can measure more than one component of flow velocity. The following equipment were purchased for this project: an Acoustic Doppler Velocimeter ($10,265) from SonTek; a low-range differential pressure transducer ($850) from Validyne; a Solo 2300 multi-media notebook ($3,600) and a HP Deskjet 670C printer ($196.43) from Gateway; a KPCMCIA data acquisition card ($701.25) and an universal screw terminal ($130) from Keithley Metrabyte.

The ADV measures all three components of velocity and can detect turbulence up a Nyquist frequency of 12.5 Hz. The velocity range of the ADV is ±2.5 m/s, and the velocity resolution is 0.1 mm/s. The apparatus uses acoustic sensing techniques to measure flow in a remote sensing volume so the measured flow is undisturbed by the presence of the probe. Several probe configurations (e.g., side looking, down looking) are available. The Validyne transducer has a full range differential pressure of 14.0 cm H_20 and a frequency response of 250 Hz. The minimum pressure range available from Validyne is 8.8 cm H_20. All the experiments were conducted in a Plexiglas walled open-channel flume. The flume is 7.62 m long, 0.61 m wide and 0.61 m deep with a flow capacity of 0.057 m^3/s. It was built in the 1960's and had been used primarily as a teaching flume. A smaller channel can also be used in these experiments. The minimum operating depth of SonTek ADV is 20-30 mm for the side-looking probe, and 55-120 mm for all other probes.

III. The Experiments

A. Flow behind a Pier

The objective of this experiment was to measure the velocity distribution and root-mean-square fluctuating velocity in the wake of a circular cylinder. The basic concepts learned were: (1) the flow behind a pier in an open channel is three dimensional and turbulent; (2) in three-dimensional flows the fluid velocities depend on all three spatial dimensions; and (3) the instantaneous velocity in a turbulent flow is consisted of a time average and a fluctuating component.

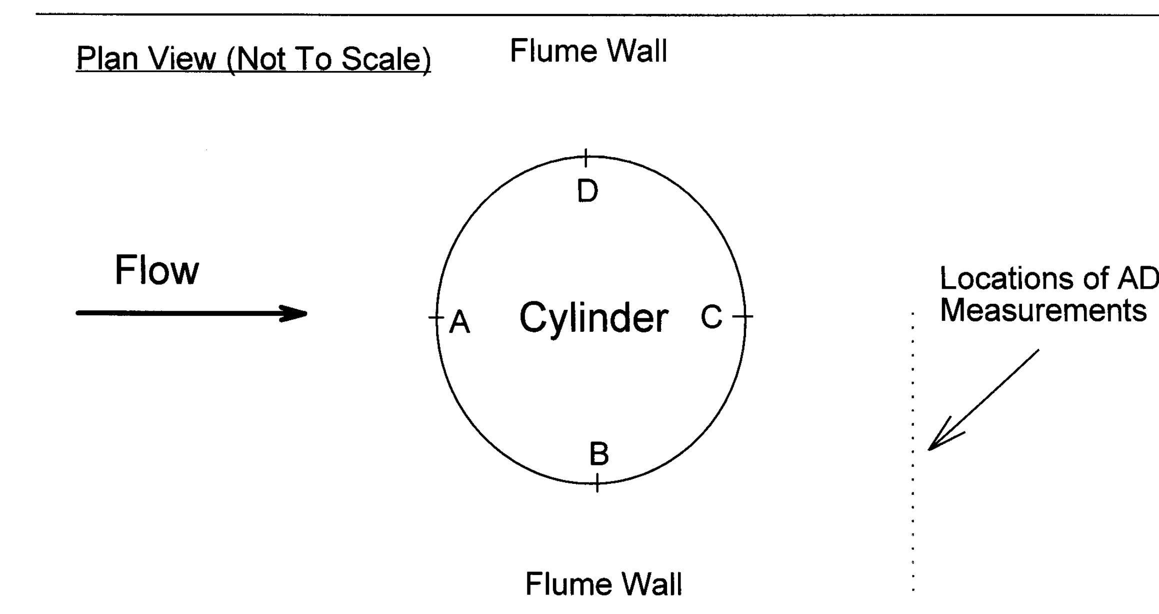

Figure 1. Schematic drawing of circular cylinder and locations of velocity and pressure measurements.

A 114-mm-diameter circular pier was placed at the centerline of an open-channel flume (Figure 1). A steady, gradually varied flow of depth 0.2 m was established by adjusting a flow control valve and a tailgate. The probe of the ADV was positioned behind the pier at mid-depth to measure velocity distribution at 8-10 locations between the centerline of the flume and one of the side walls. At each location, 100-second-time histories of the longitudinal, transverse and vertical velocity components (u, v, w) were taken. Students analyzed the measured velocity-time records and obtained all three components of mean velocity and root-mean-square fluctuating velocity.

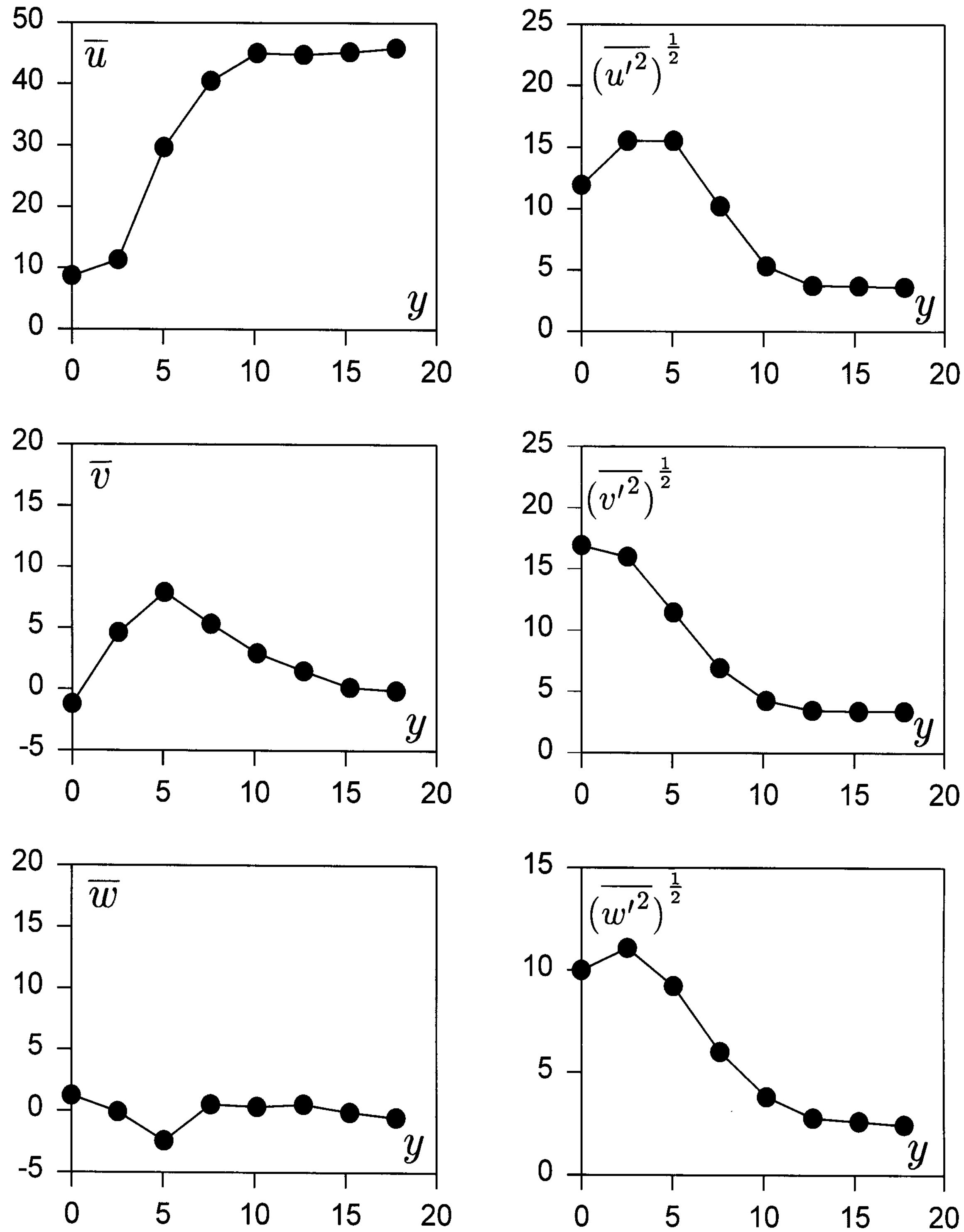

Figure 2. Variations of mean velocity and root-mean-square fluctuating velocity (in cm/s) with distance (in cm) from center of circular cylinder.

In the laboratory reports, students plotted the mean velocity and root-mean-square fluctuating velocity components as a function of distance from the centerline of the flume (Figure 2), and discussed how these flow quantities varied across the wake of the pier. Figure 2 showed that: (1) due to the presence of a pier the longitudinal velocity was very small directly behind the pier. The longitudinal velocity increased steadily with distance from the pier and became almost uniform outside the wake; (2) as the flow moved around the pier the transverse velocity was a maximum near the edge of the pier and decreased steadily toward the centerline and side wall of the flume; (3) the vertical velocity was non-zero inside the wake but it was nearly zero in the free stream; and (4) all three components of root-mean-square fluctuating velocity decreased with distance from the pier.

B. Pressure Distribution on a Circular Cylinder

The objectives of this experiment were: (1) to calibrate a DC voltage output pressure transducer for measurement of differential pressure, and (2) to measure the differential pressure between the front and the side, and between the front and the back of a circular cylinder in a turbulent open-channel flow. The basic concepts learned were: (1) in an inviscid flow the fluid velocity on the cylinder's surface would vary from zero at the front and rear of the cylinder to a maximum of $2U$ at the sides of the cylinder, where U is the velocity of the approach flow; (2) from the Bernoulli equation the differential pressure between the front and the back of the cylinder would be zero and the differential pressure between the front and the side of the cylinder would be $2\rho U^2$, where ρ is the fluid density; and (3) friction and flow separation cause the pressure at the rear of the cylinder to be less than that at the front, and the differential pressure between the front and the side of the cylinder to be less than that predicted by inviscid theory[1].

The transducer was calibrated by connecting its positive and negative pressure ports to two piezometer tubes; changing the water level differential between the two tubes at equal increments from 0 mm to 140 mm; and recording the corresponding transducer voltage outputs. The experimental setup in the flume was the same as in the previous experiment. The circular cylinder had four tapping holes A, B, C and D spaced at 90° around its circumference (Figure 1). The transducer was first connected to tapping holes A and C at the front and back of the cylinder. A time record of the transducer voltage output was recorded using a multimeter. The transducer was then connected to the tapping holes at the front and sides of the cylinder (A and B, and A and D), and the voltage outputs were again recorded. The ADV was positioned in front of the cylinder to measure the approach flow velocity. The measured velocity was 0.48 m/s. Students observed that in a turbulent flow, pressure as well as velocity fluctuated with time.

In the laboratory reports, students plotted a calibration curve for the pressure transducer (Figure 3) and used this calibration curve to convert measured voltage into pressure (Table 1). These measurements were compared to the theoretical results obtained based on the Bernoulli equation. Table 1 showed that the pressure at the rear of the cylinder was less than that at the front, and the pressure at the two sides of the cylinder were about the same. In addition, the differential pressure between the front and the side of the cylinder was less than $2\rho U^2$, the value for ideal flows.

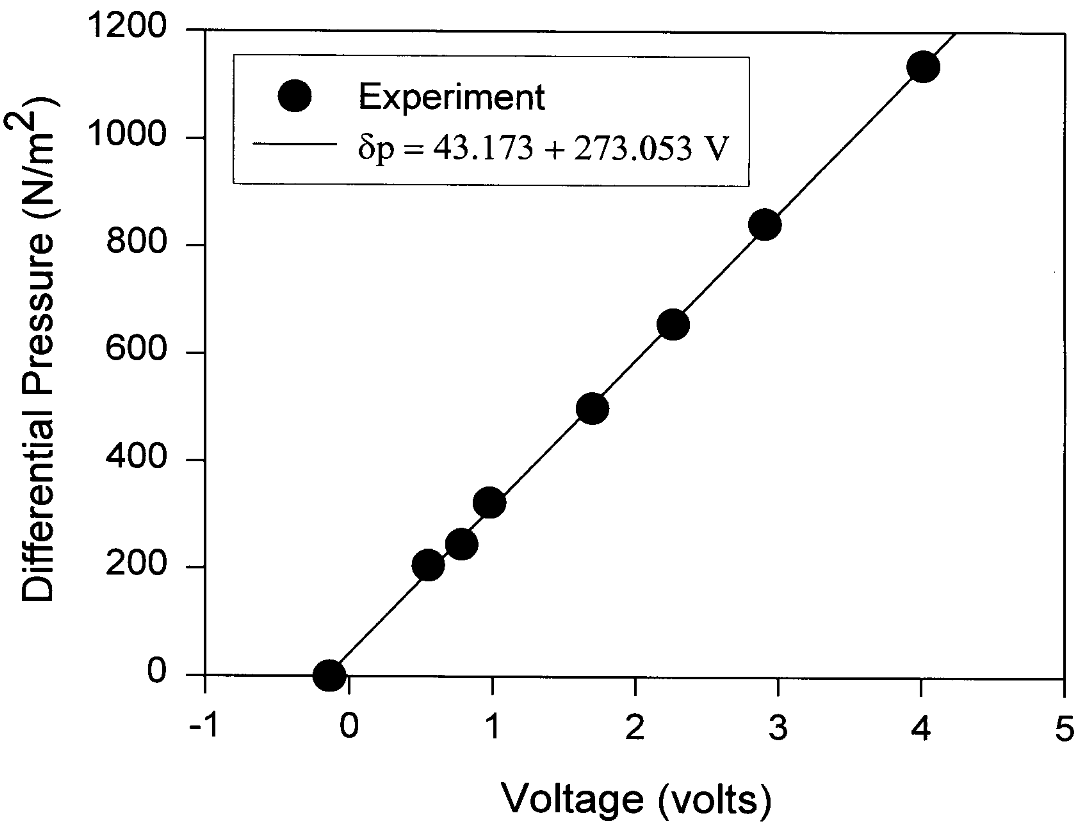

Figure 3. Calibration of pressure transducer.

Location	Voltage, volts	Differential Pressure (Experiment), N/m^2	Differential Pressure (Ideal Flow), N/m^2
A-B	1.06	332.61	460.8
A-C	0.003	43.99	0.0
A-D	1.04	327.15	460.8

Table 1. Measured and computed differential pressures.

C. Reynolds Stress

The objective of this experiment was to measure the Reynolds stress components in a simple shear flow and to study their characteristics. The concepts learned were: (1) turbulence is three dimensional even though the mean flow is one dimensional, (2) Reynolds stress is much larger than viscous stress in a turbulent flow, (3) the large-scale turbulence is not isotropic, and (4) the correlation coefficient for Reynolds stress is around -0.4.

A steady, gradually varied flow was established in the flume. The water depth was 0.2 m and the free-stream velocity was about 0.5 m/s. The ADV was positioned at the centerline of the flume where the flow was very nearly one-dimensional. The ADV was used to measure all three components of instantaneous velocity at 8-10 locations over the water depth. Data were recorded for 300 s at 25 Hz per channel. The data were analyzed to obtain the time average velocity and root-mean-square fluctuating velocity components, as well as the Reynolds stress and Reynolds stress coefficient in the vertical plane parallel to the flow. Viscous shear stress was calculated from the measured mean velocity gradient using Newton's law of viscosity. All the results were plotted as a function of water depth.

From these results, students observed that all three components of root-mean-square fluctuating velocity were non-zero but only one of the mean velocity components (the longitudinal component) was not equal to zero. However, the longitudinal component of root-mean-square fluctuating velocity was larger than the transverse and vertical components. It was also shown that the Reynolds stress was about 10^5 times larger than the viscous shear stress outside the bottom boundary layer. Finally, it was found that the value of Reynolds stress coefficient was about –0.4 in the boundary layer and decreased with distance from the flume bed.

D. Velocity Distribution in Open-Channel Flow

The objective of this experiment was to measure the velocity profile in the near-wall region in a turbulent open-channel flow and to compare the measured profile with the logarithmic law[1]. The concept learned was the structure of wall boundary layer. The experimental procedure was essentially the same as in the previous experiment except that all the velocity measurements were taken within 20% of the water depth from the flume bed. The time average longitudinal velocity was plotted against the distance from the flume bed in a semi-log plot. The curve was nearly linear in the region close to the bed but deviated from a straight line further away from the bed. The friction velocity was obtained from the semi-log plot and used to estimate the bed shear stress.

IV. Impact of the Project

The above four experiments were conducted in two undergraduate classes (CEE 331 Fluid Mechanics Laboratory and CEE 493 Environmental Fluid Mechanics). CEE 331 is required of all civil engineering students and is offered in both fall and spring semesters. CEE 493 is a technical elective and is offered only in the spring semester. These experiments were first introduced in spring 1997. Between January 1997 and December 1998 a total of 95 undergraduate students had carried out one or more of the above experiments. In addition, one undergraduate student, Angeline Teng, used the project equipment to conduct an independent study on turbulent flow around a circular cylinder during the fall and spring semesters in 1997. She was the co-author of a paper[3] presented at the 12th Engineering Mechanics Conference in San Diego, California on May 17-20, 1998.

A questionnaire was prepared and sent to all the students who had taken the two classes mentioned above. Completed surveys were received from 57 students. Almost all of the students strongly agreed or agreed that their understanding of basic fluid mechanics principles were improved by this project, and that this project had enhanced their interests in fluid mechanics. Many students also expressed an interest in pursuing advanced study or research in engineering. The author is currently constructing a homepage on the World Wide Web for dissemination of research and education activities related to the Fluid Mechanics Laboratory at South Dakota State University. This homepage will be linked to the College of Engineering homepage (http://www.engineering.sdstate.edu). Results of all the experiments described in this paper will be available from the homepage in summer 1999.

V. Acknowledgments

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