Chapter 2 Apparatus and Instrumentation

2.1 Wind Tunnel

Measurements where made in the Virginia Tech 3' x 2' subsonic wind tunnel shown in figure 2.1. The air is pulled through the tunnel by a 12 flat bladed fan powered by a 30 hp 3-phase motor (Engel & Devenport, 1995). The air enters through a bellmouth inlet and passes through a settling chamber with contraction ratio of 16:1 before it enters the test section. The test section measuring 20'11" long, 3' wide and 2' high is made of wood and Plexiglas. Reference velocity is provided through a Pitot-static tube located 3" downstream of the test section entrance.

The settling chamber, with a contraction ratio of 16:1 measuring 12' wide by 8' tall and 3'3" long, is made of heavy gauge sheet steel. A bellmouth made of thin gauge rolled sheet steel is attached to the outermost part of the settling chamber. This prevents any separated flow from entering the tunnel. The bellmouth sections are similar in shape on all sides except on the floor, where a truncated shape is used.

In order to reduce free stream turbulence levels and flow angularities, a series of seamless and seamed screens are installed with nominal separation of 6" between successive screens. The honeycomb screen is made of aluminum foil hexagonal shape of .0007" thickness. The size of the honeycomb was chosen so as to get the best flow angularity with the least amount of blockage effect. The hexagonal honeycomb provides with a 4.95 degrees maximum allowable flow angularity with porosity ratio of only 0.54%.

The test section of the wind tunnel is 3 feet wide by 2 feet high, and 20'11" long as shown in figure 2.1. The test section is made of Plexiglas and wooden walls. The wooden walls, floor and ceilings are made of plywood of 3/4" thick, and the clear Plexiglas is also 3/4" thick. The inside of the test section comprises 1/4" thick hardboard. A 5" x 5" Plexiglas viewports are located near the entrance of the test section on the right side wooden section sidewalls looking downstream.

The test section is aligned with the diffuser but is not physically attached to the diffuser in order to prevent vibration induced in the diffuser section. A silicon rubber sealant is used to fill the gab between these two sections.

The diffuser section with a contraction ratio of 1:1.6 and measuring 6' 2" long is constructed of sheet metal and angle iron. To reduce any movement due to the vibration, the diffuser is bolted to the floor. Just inside the diffuser, a honeycomb made of 1.5" diameter cardboard tubes of length 6" were epoxyed together prevents propagation of upstream effects of swirling flow induced by the fan blades.

The air is pulled through the tunnel by a 12 flat bladed fan powered by a 30 hp 3-phase motor operating at 1765 rpm. The motor was built by Twin City Fan & Blower Co., Minneapolis, Minn. The section housing the motor is constructed from thick gauge sheet steel welded at the seams and bolted down to the floor to inhibit any movement due to vibration.

Flow speed is controlled using the blower exit vanes. The speed can be adjusted up to maximum speed of 26 m/s. and can be increased even further to a top speed of almost 30 m/s by removing the vanes completely, as was done for our experiment.

The flow is uniform across the potential core with turbulence level of approximately < 0.2%.

2.2 Pressure Gradient Measurement

The pressure gradient due to the boundary layer growth in the tunnel test section, which could affect wake growth, was eliminated by installing tapered fillets at the corners of the test section. Cross-sectional views of the upstream fillets are shown in figure 2.2. The fillets were cut from polystyrene foam using a hot wire foam cutter, covered with clear plastic Con-tac paper, and attached to the corners of the section using silicon sealant. The fillets were shaped so that the rate of diffusion would cancel the acceleration of the flow caused by the growing boundary layer. Small curved fillet sections provide smooth transition at the forward edge of the most upstream fillets and at the trailing edge of the downstream fillets. Once the fillets were installed, measurements on the streamwise pressure were conducted in the empty test section. Figure 2.3 shows the normalized pressure coefficient, Cp versus streamwise distance *x* in feet measured from the entrance of the test section. Also included in the plot are the locations for the single point measurements. The pressure gradient in the test section was reduced to a value $\partial C_p/\partial x$ of about 5×10^{-4} per foot.

2.3 Wake Generator Models

2.3.1 Circular Cylinder Model

The circular cylinder model, a straight cylindrical 3/16" stainless steel rod spanning the width of the tunnel midway between the tunnel roof and floor, was mounted horizontally from the wind-tunnel sidewalls. The aspect ratio of the cylinder (span/diameter) was 192. The cylinder was mounted perpendicular to the flow direction to an accuracy of better than 0.1 degrees.

2.3.2 Ring Model

The toroidal ring model with inside and outside diameters of 5.8125" and 6" respectively was made from 3/16" brass rod. The brass rod was bent to form a ring then butt soldered at the ends and filed smooth. The ring was mounted in the center of the tunnel test section using 5/1000" fishing line attached at four points around the periphery of the ring (figure 2.4). The line, extending upstream and downstream of each attachment point at an angle of 20 degrees to the flow direction, secured the ring to the four walls of the test section. A dowel pin and turnbuckle arrangement allowed these support wires to be placed under tension to eliminate any visible flow induced vibration in the ring. The plane of the ring was placed perpendicular to the tunnel flow direction to an accuracy of 0.2 degrees. The Reynolds number based on the diameter of the fishing line and the free-stream velocity component perpendicular to it would have been about 73. Unfortunately this is larger than the Reynolds number at which shedding begins to occur. However, given the small diameter of the line we still expect that the steady and unsteady influence on the ring wake would have been small.

2.4 Pitot-Static Tube

Reference Pitot-static tube was mounted 17.5" from the test section entrance, 6" from the ceiling, and 6" from the left inside wall looking downstream. Pressure transducers having 0-5V range were used to determine freestream velocity. Reference pressure output from the transducers is input in to an A/D board and a computer.

2.5 Hot-wire anemometry

Velocity measurements were made using a miniature Kovaznay type four-sensor hot-wire probe manufactured by Auspex Corporation (type AVOP-4-100), shown in figure 2.6. The tip of the hot-wire probe consist of eight stainless steel tapered prongs (75μm in diameter at their tips) that hold the sensor wires some 40 mm upstream of the main part of the probe. The sensor wires are made of etched tungsten wire of 5 mm diameter and approximately 0.8 mm in length with length to diameter ratio of 160. The wires are arranged in 2 orthogonal X-wire arrays and are inclined 45° to the probe axis. The total measurement volume is approximately 0.5 mm^3.

Each of the sensor wires was handled by using a Dantec 56C17 bridge and a Dantec 56C01 constant temperature anemometer unit. The bridges were optimized to give a frequency response greater than 25 kHz. Output voltages from the anemometer bridges were amplified by a x10 buck-and-gain amplifiers with calibrated RC-filters to limit their frequency response to 50 kHz. The amplified signal was then recorded by an IBM AT compatible computer with an Analogic 12 bit HSDAS-12 A/D converter. The A/D converter also sampled output voltages from a pressure transducer reading reference dynamic pressure and a digital thermometer reading flow temperature.

The hot-wire was calibrated for velocity before and after each measurement using a TSI model jet calibrator. The hot-wire is placed in the uniform jet and correlation between output voltage and cooling velocities is obtained according to King's law. Direct angle calibration (DAC) is performed to obtain flow angle of the velocity components from the cooling velocities. The DAC is performed by placing the hot wire in the uniform jet and maneuvering it to all possible flow angle combinations from +45° to -45° of yaw and pitch. By comparing the known yaw and pitch angles from the probe output, the relationship between cooling velocities and flow angles is determined. Ambient temperature drift of the hot-wire signals was corrected for using the method of Bearman (1971).

The DAC was conducted at a constant velocity. This implies that the calibration is independent of velocity, which isn't true. However as Wittmer (1996) shows the variation of the DAC at selected points in the range of velocities between 19 and 34 m/s — which is the range measured in this study — is less than 1%.

Since measurement of two-point cross spectrum between a pair of points was part of the scheme, the hot-wires needed to be optimized such that the frequency response of each sensors of the probe be closely matched. In order to inspect the frequency response of each probe, a pulsed YAG laser was used. Each sensor, placed in a flow having the same velocity as that for the experiment, was pulsed by the laser that lasts for nano-seconds at a rate of about 10Hz. The signal output from the anemometers, revealing the impulse response of the system, was recorded using a Rapid Systems R2000 8-bit 20Msample/sec A/D converter system. The impulse response signals were phase aligned using the trigger signal from the laser and recorded over many realizations to obtain an average of the behavior. The data was then Fourier transformed to obtain the characteristic phase and frequency response of the sensors. It was found that the form and shape of the optimized frequency response of the sensors depends on the length of the probe cables. By adjusting the length, frequency response of the each sensor shown in figure 2.7 was obtained. The result shows flat amplitude response well beyond 20kHz, which is above the requirement for present turbulence measurements which show the energy level to be negligible beyond about 13kHz.

2.6 Traverse System

Two types of traverse systems were used. A single axis traverse system was used to measure the single point velocity profiles. The traverse is placed on a rail (scaled to millimeters) to move it in the streamwise direction shown in figure 2.8. The rail is screwed in to the tunnel floor.

An external two-axis computer-controlled traverse clamped on top of the tunnel structure was used to measure cross sectional measurements at two stations. Two stepper motors manufactured by Compumotor (model S57-83-MO) were used to control the movement for each of the axis. The motors were mounted on a TechnoIsel double rail guiding system. These guiding screws which are driven by the motors were made by TechnoIsel and are accurate to 0.003" per foot. This system setup was mounted on aluminum I-beam (figure 2.9). During measurement, the whole traverse is set placed on top of the tunnel. To prevent metal-to-metal contact and also to reduce vibration, the traverse is placed on top of a 1" x 6" x 96" hard wood board.

2.7 Measurement locations

The two-dimensional cylinder and the ring models were both placed at the same streamwise location, 80” downstream of the test section entrance. Measurements were made for an approach free-stream velocity U_∞ of 27.7m/s. Velocity profiles were measured through the wakes of both models at 20 streamwise stations in the range of $50 \leq x/d < 500$ (where x is measured downstream from the cylinder or toroid center). Profile measurements were made using a single axis sting-mounted traverse. For the plane wake traverses were made along vertical lines perpendicular to the plane of the wake. For the ring wake, traverses were made along lines measured radially outward from the axis of the toroid at an angle of 30 degrees to the horizontal, this being well away from the from the wakes of the horizontal and vertical wire supports.

Measurements were also performed in grids to reveal the complete cross-sectional structure of the cylinder and ring wakes x/d = 126 and x/d = 450. These measurements were carried out using an external two-axis computer-controlled traverse clamped to the tunnel superstructure. Two-point 3-component measurements were also made in cross-sectional grids (figures 2.10 (a) and (b)) at x/d = 126 and x/d = 450 to obtain cross-correlation data in order to analyze the turbulent structure of both flows.