Mapping the Flow Characteristics of the Baylor University Wind Tunnel

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Abstract

The purpose of this experiment was to capture and analyze the flow characteristics of Baylor University's subsonic wind tunnel to determine the uniformity of both velocity and turbulence intensity in the test section. Tunnel flow was accelerated to 15 meters per second and a square-mesh, square bar turbulence generation grid was inserted perpendicular to the flow. The tunnel has a cross section of 8" by 12" inches. Three cross-sectional areas located 23.25, 30.875, and 38.5 inches downstream of the grid were surveyed for uniform velocity and turbulence intensity. The turbulence decay with distance from the grid was evaluated by taking ten data points along the length of the test section beginning 18.25 inches downstream from the grid and spaced 2.5 inches apart. Velocity and turbulence intensity measurements were performed using a TSI IFA 300 Anemometer System. A region of uniformity measuring 4.25 inches high and 2.125 inches wide centered in the tunnel cross-section was located in the test section between 30.875 and 38.5 inches downstream of the turbulence generation grid. A deviation of 5-10 percent from average velocities and turbulence intensities was observed around the edges of the cross-sections. The slightly accelerated flow occurred because the turbulence generation grid design caused a reduced resistance near the tunnel walls. Design of the turbulence generation grid could be improved by adding bars to the outside edges of the grid to create more uniform flow around the edges of the cross-sections. The turbulence decay along the length of the tunnel behaved in accordance with downstream turbulence decay predictions of Roach[1] with the exception of a one-percent increase in TI. Some investigation was accomplished on experimental techniques, data acquisition methods, and the evaluation of parameters required to capture the appropriate frequency range of the data (i.e. integral-length scales).

Introduction

It is important with any wind tunnel to be able to characterize the flow characteristics present in the test section. Understanding qualities such as flow velocity and uniformity, as well as turbulence levels, enables a better understanding of the test environment. This leads to better experimental planning. An elevated freestream turbulence level is sometimes desirable as the effects of turbulence on heat transfer and boundary layer transition are becoming more widely investigated experimentally. Experimental data often provides the basis for computational modeling and, in order to model the flow correctly, the flow must be fully characterized. The purpose of this experiment was to analyze the flow characteristics of Baylor University's subsonic wind tunnel to determine the uniformity of both velocity and turbulence intensity in the test section to include micro and macro length scales. The results of this study will provide specific values of flow quality downstream of the turbulence generation grid at three different locations. This will show uniformity of both the flow velocity and turbulence intensity, as well as show the decay in turbulence intensity downstream of the turbulence generation grid. Insights gained from this study will suggest improvements to both the turbulence generation grid and the wind tunnel itself. In summary, two major questions were explored during this experiment: 1) is the flow at a given cross-section of the tunnel both uniform in velocity and turbulence intensity and 2) is the turbulence downstream of the turbulence generation grid decaying as expected? These two questions were evaluated by comparing the data from this experiment with the results presented in Roach[1].

Background and Theory

Turbulence intensity, or TI, is a measure of the level of turbulence present in the flow. TI is defined as the square root of the mean square of the fluctuating velocity divided by the time-averaged velocity, or

$$TI = \frac{\sqrt{\left(\overline{u}'\right)^2}}{\overline{u}} \qquad \textbf{(1)}$$

where $\overline{u}'$ is the fluctuating velocity and $\overline{u}$ is the time-averaged velocity. Turbulence intensity is important in this experiment because it quantifies the effect of the passive grid on the velocity fluctuations.

Characterization of the flow in the Baylor University wind tunnel had not been accomplished previously; thus, developing an experimental method to acquire the velocity and TI data was necessary. Simon et al.[2] suggested a method to determine sample frequency and size that was used in this experiment to acquire data. The methods presented by Simon et al.[2] utilize a Power Spectral Distribution plot and autocorrelation to select appropriate sampling frequency and size to collect accurate data and determine the integral-length scales.

Power Spectral Distribution and Autocorrelation

The Power Spectral Distribution (PSD) is a function that displays the distribution of the signal frequencies present in the sample (see Fig 1). An accurate plot of the PSD requires that the appropriate frequencies in the signal be captured; in essence, rapid sampling rates will capture the smallest frequencies and long sampling durations will capture the large frequencies. The PSD is developed by using a Fast Fourier Transform (FFT) on a specified number of data points, or block of data, and the results from each block of data are averaged into one combined spectrum. The power spectrum increases in accuracy as the number of data points per FFT

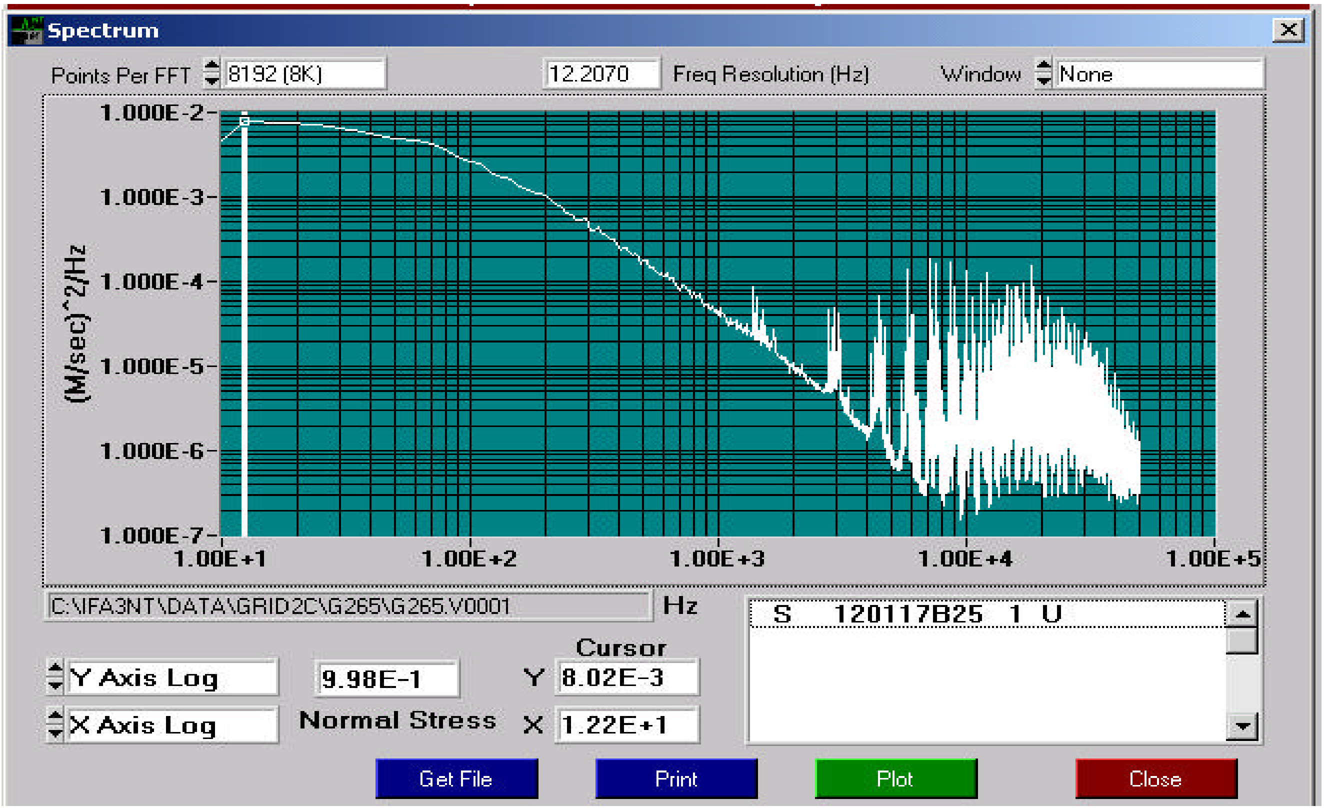

Figure 1. Example of a Power Spectral Distribution Plot

increases. The software used to process the data, provided with the TSI IFA 300 Anemometer, had a maximum block size of 256K.

The PSD was also used to determine the correct choice of a low-pass filter. From looking at the plot, choosing a filter between 10 kHz and 50 kHz would satisfactorily capture the required signal information for a velocity of 15 m/s. The software program had only three low-pass filter settings within this range of frequencies: 10, 20 and 50 kHz. A filter size of 20 kHz was used for this experiment because it represented a mid-range low-pass filter. Suggestions for sampling frequencies vary anywhere from two to five times the low-pass filter setting. Two times the filter setting satisfies the Nyquist criterion; whereas, Simon et al.[2] and Roach[1] suggest using five times the low-pass filter setting to have more confidence in capturing a complete signal. Thus, five times the low-pass filter setting was initially chosen as the sampling frequency rate and duration for the experiment. As a result, the sample rate used in this experiment was 100,000 samples per second. The IFA 300 is capable of sampling up to 300 kHz.

The autocorrelation is the correlation of the velocity signal with itself displaced by a period, T (see Fig. 2).

$$R(T) = \frac{\left(u'(t) * u'(t-T)\right)}{\left(\overline{u}'\right)^2} \quad \textbf{(2)}$$

where t is the time at which the measurements were taken. The software program creates the autocorrelation by processing a block of data and averaging the blocks into a composite autocorrelation. The preciseness of the autocorrelation increases as the number of points per block increases; yet, the processing times also increase significantly as the number of points per block increases. The maximum number of points per block allowed by the software, 256K, was used for the autocorrelation of this experiment. The integral of autocorrelation is used to compute the macro and microscales, both of which are related to the size of vortices present in the flow. The autocorrelation is integrated from zero out to the first zero crossing in order to capture both the finest and the largest scales. Thus, defining an appropriate sample frequency and duration is required to properly calculate the length-scales. An adequately large sampling rate is required to capture the micro-length scales, and a longer duration is needed to capture the macro-length scales. An iterative process is used to determine a compromise between the rate, duration, and disk space size. The compromise should not sacrifice result accuracy, but it should keep in mind the length of times needed for disk sizes and data processing times. Simon et al.[2] have developed guidelines to help determine an appropriate compromise between the sample rate, duration, and disk space.

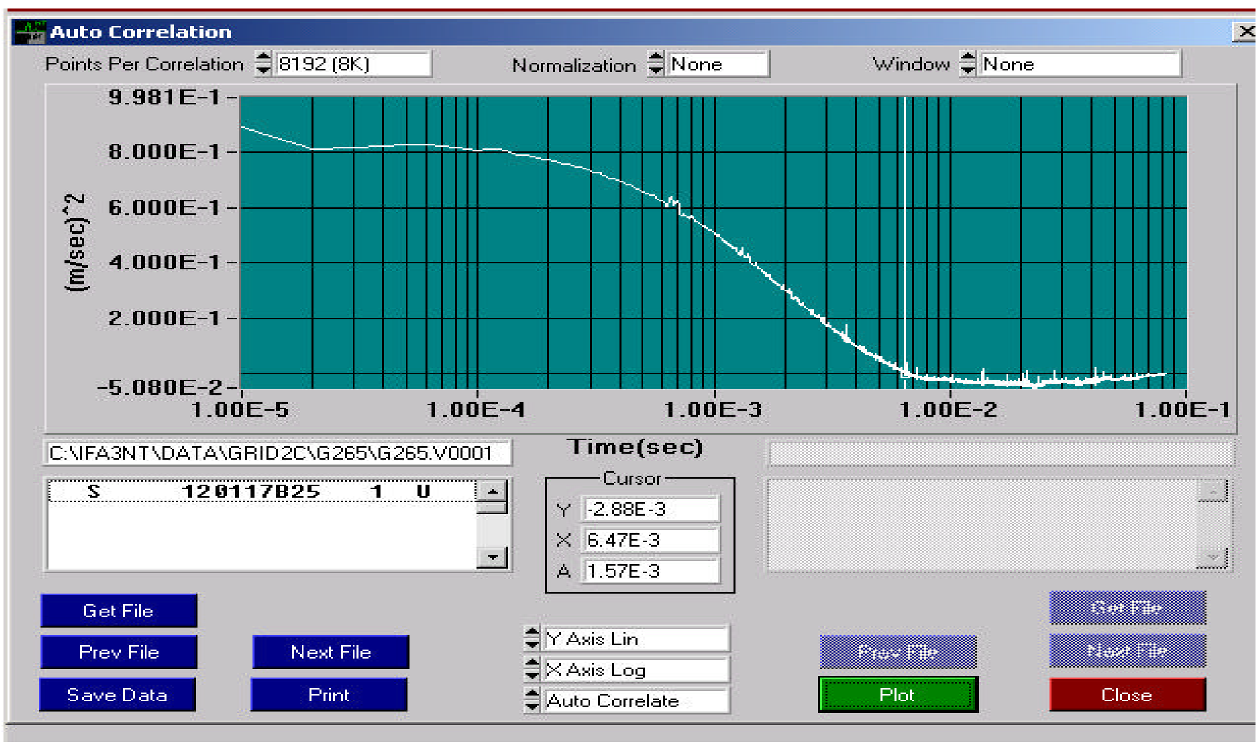

Figure 2. Example of an Autocorrelation

Micro and Macro-Length Scales

The key to calculating proper integral-length scales is to use an iterative process for choosing the desired sampling rates and times for the experiment. These choices lead directly to considerations for data storage and processing times. Roach[1] states that the macro scale, ?, is reflected by the largest eddy size in the turbulent flow; therefore, he suggests beginning the iteration with a macro scale size equal to the largest grid dimension size (the diameter or width of the bars of the passive grid). The Simon et al.[2] suggest that the time duration be calculated from the macro scale using

$$t \rangle 6000 * \frac{\Lambda}{\overline{u}} \tag{4}$$

where t is the total sample time and u is the mean velocity. Consequently, the micro scale, ?, is computed using

$$l = \sqrt{\frac{(10 * \Lambda * n)}{(TI * \overline{u})}} \tag{5}$$

where ? is the macro scale, ? is the kinematic viscosity, TI is the turbulence intensity, and u is the mean velocity. The filter frequency may also be estimated using

$$f_{filter} \rangle 4 * \frac{\overline{u}}{l} \tag{6}$$

The preliminary evaluation of these equations estimates an initial value for the macro and micro-length scales, filter frequency, rate, and duration. An initial set of data was taken and processed using these criteria, and then the actual macro and micro scales were calculated. These “new” values for the macro and micro scales were used in the second iteration. The iteration process was repeated until a consistently recurring filter frequency, sampling rate, and duration was established; consequently, these parameters were used to capture data from the test section.

Experimental Apparatus

Baylor University Wind Tunnel

The Baylor University Wind Tunnel is an open loop tunnel with a test cross-section measuring 8x12x48 inches. Operating speeds of up to 25 m/s are possible and are automatically controlled by a computer interfacing with a variable speed controller. Pitot-static measurements were made in the test section at a location 30 inches downstream from the turbulence generation grid. A TSI IFA-300 anemometer was used to acquire the velocity and turbulence data and the IFA-300 software was used to evaluate the velocity readings and compute the turbulence intensity, power spectrum, and autocorrelations for the data. Typical velocity accuracies for the IFA 300 are quoted as 0.5% and accuracies of turbulence intensities at 0.3%. Sample rates of 300 kHz are possible. A manual three-axis traverse was used to position the hot-film in the test section.

Turbulence Generation Grid

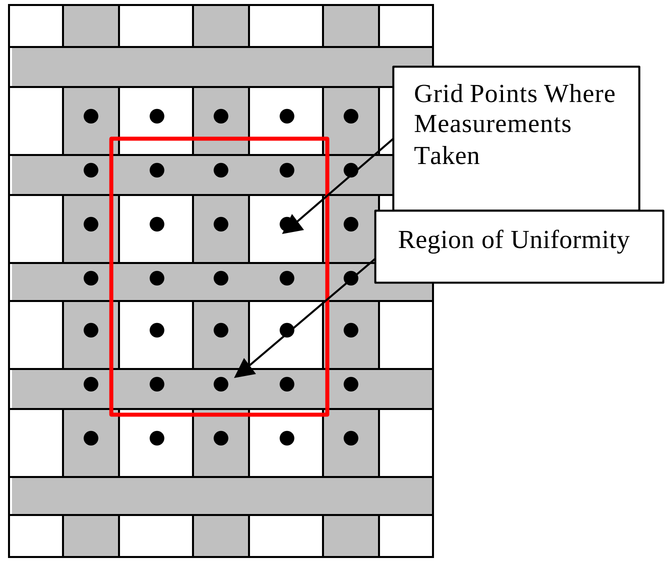

Figure 3. Measurement Locations for Grid#3 and Area of Uniformity

The turbulence generation grid was modeled as a square-mesh array of square bars, or SMS grid, described by Roach[1]. The diameter of the square bars was 0.405 inches and the grid porosity, ß, was 0.704. The grid was placed in the tunnel perpendicular to the flow and located at the entrance to the test section to produce homogeneous flow in the test section (Roach[1] indicates that "there is an initial distance in the immediate wake region downstream of a grid where the flow is strongly inhomogeneous"). The turbulence micro and macro scales were determined using the data taken from three cross-sections in the test section: 23.25, 30.875, and 38.5 inches downstream of the grid. In addition, the downstream turbulence decay was evaluated by taking ten data points along the length of the test section beginning 18.25 inches downstream from the grid and spaced 2.5 inches apart.

Experimental Methods

Measuring Pressure in the Tunnel

Measurements of velocity were made using a Dwyer Microtector Portable Electronic Point Gage Micromanometer. The micromanometer has a stated accuracy of 0.00025 inches of water and is the least sensitive of the gages to small fluctuations in pressure. The repeatability of the measurements using the micromanometer was extremely good and ensured capturing the data at a steady 15 m/s.

Measuring the Velocity and Turbulence

The mean velocity and turbulence measurements were made at each point using the TSI IFA 300 Anemometer coupled with the acquisition and analysis software. The IFA 300 is capable of sampling at 300 kHz. The TSI Calibration System Model 1129 was used to calibrate the hot-film over a velocity range from 1.5 to 25 m/s. A King's Law relationship provided an excellent data fit having a mean squared error (MSE) of 0.00006. As a result, typical uncertainties in velocity are 0.5% and for turbulence intensity 0.3%. The data acquisition process of this experiment utilized a filter size of 20 kHz, sampling rate of 100 kHz, and duration of 20.9715 seconds. These values were previously determined as the best combination of filter frequency, sampling rate, and duration for a tunnel velocity of 15 m/s. This combination of parameters was used to measure the velocity and TI values for three grid areas and along the centerline of the tunnel (see Fig. 3).

Results and Discussion

Uniform and Isotropic Flow Analysis of Tunnel Cross-Sections

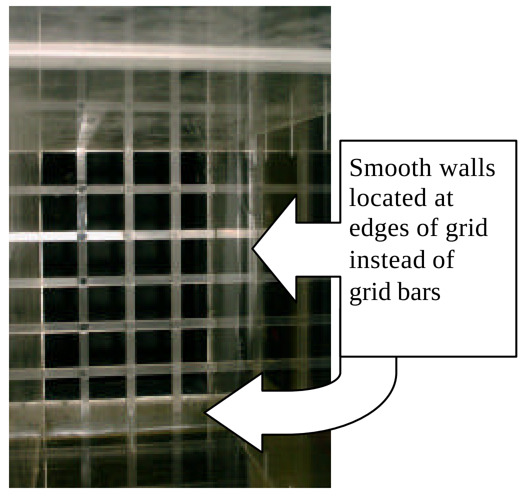

Figure 5. Turbulence generation grid with smooth walls of wind tunnel for edges

The data were taken at three grid locations and analyzed for uniform and isotropic flow. Fourteen data points were taken for the grid closest to the turbulence generation grid (Grid#1), 33 points were taken for the middle grid (Grid#2) and 35 points were taken for the furthest downstream grid location (Grid#3). Three-dimensional plots were created for each grid of the velocity and TI at each data point. A typical example of a three-dimensional graph is shown in Figure 4. An area of uniformity was determined by comparing the measured velocities and TI for each grid with the average velocity and TI from each grid. Percent deviations ranged from 0.11 percent to 9.2 percent, with only one point having a deviation greater than 9.2 percent (TI point (7,3) on Grid#3). The velocity distributions for Grid#2 and Grid#3 reveal that the outer edges of the grids have slightly increased velocities, which deviate from the average velocity by a maximum of 9.2 percent. The slight increase in velocity is attributed to lower resistance created by the smooth walls around the tunnel. The square-mesh, square bar grid design uses the smooth tunnel walls for its outer edges instead of grid bars (see Fig. 5). The insertion of bars along the edges of the grid would produce obstructions in the flow around the tunnel walls and reduce the size of the velocity jets in the downstream flow that caused higher velocities than the average. Grid#2 and Grid#3 exhibited uniform velocity and TI around the same cross-sectional region because both grids had velocity and TI data that deviated from the average by less than 6.5 percent in an area 4.25 inches high and 2.125 inches wide. Grid#1 exhibited deviations from average by less than 6.2 percent; however, the complete set of data points for the 4.25 inch high, 2.125 inch wide area were not taken for this cross-section. Since only Grid#2 and Grid#3 contained the data in this region of uniformity, it is recommended that experiments be conducted in a test section located between 30.875 and 38.5 inches downstream of the turbulence generation grid. Because of the slight increase in the velocity measurements near the outer edges of the cross-sectional grids, it is also recommended that the useable area at this location be limited to a height measuring 4.25 inches and a width measuring 2.125 inches centered in the test section.

Turbulence Intensity Dependence on Filter Size

The dependence of TI on filter size was noted using three filter sizes of 10k, 20k, and 50 kHz at sampling rates from 50k to 200 kHz and durations ranging from 5 to 200 seconds. As the filter size increased, the TI increased almost proportionally. To better clarify this dependence of filter frequency upon TI, seven samples of filter frequencies ranging from 10Hz to 50kHz were taken at a 10Hz rate for a six-minute duration. Looking at Fig. 6, the range from 300 Hz to 20 kHz appears to be a constant with about an eight-percent difference in TI from 300 to 20 kHz. Less than a ten-percent difference in the dependency indicates that a choice of filter frequencies between 300 Hz and 20 kHz would be an adequate selection of filter size to minimize filter and TI dependency. Thus, 10 kHz appears to be the best selection of filter size; however, 20 kHz was used for the experiment to ensure that most of the higher frequencies were present. Velocity versus filter frequency was also compared in this graph; however, the constant plot of the velocity versus filter frequency suggests there is no dependence between the two.

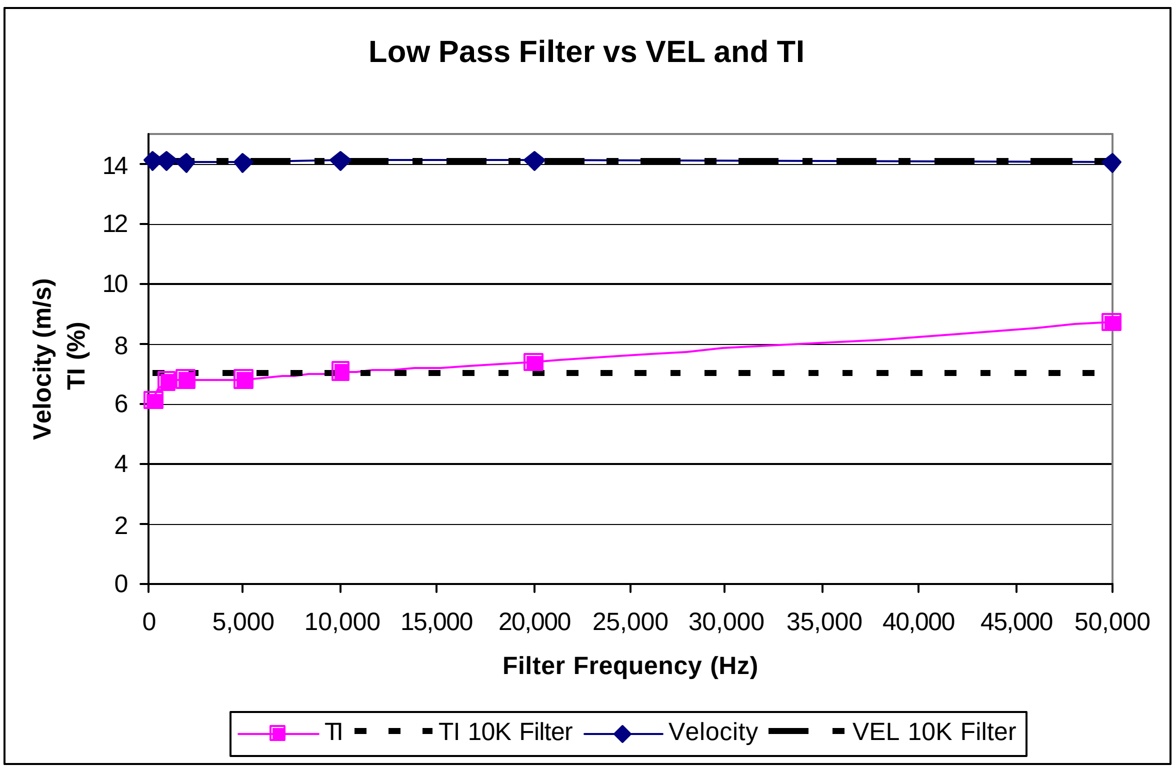

Figure 6. Velocity and TI Dependence on Low-Pass Filter Frequency

Turbulence Decay

A series of ten data points were taken along the centerline of the tunnel test section. The nearest data point was taken 18.25 inches downstream of the turbulence generation grid and the farthest was taken 40.75 inches from the grid. Roach[1] stated that the streamwise component of the turbulence intensity, *TI*, should follow the equation

$$TI = C * \left(\frac{x}{d} \right)^{\frac{-5}{7}} \tag{3}$$

where x is the distance downstream of the grid, d is the representative grid dimension (in this case it is the width of the grid bars), and C is a constant based upon grid geometry and Reynolds number (the grid used modeled a square-mesh array of square bars, or SMS grid, where C=1.13 was experimentally determined by Roach[1]). Figure 7 plots the two turbulence decay equations.

The trendline shows consistently higher TI values for the present experiment of about one percent. Reasons for the differences from the Roach prediction need to be explored further.

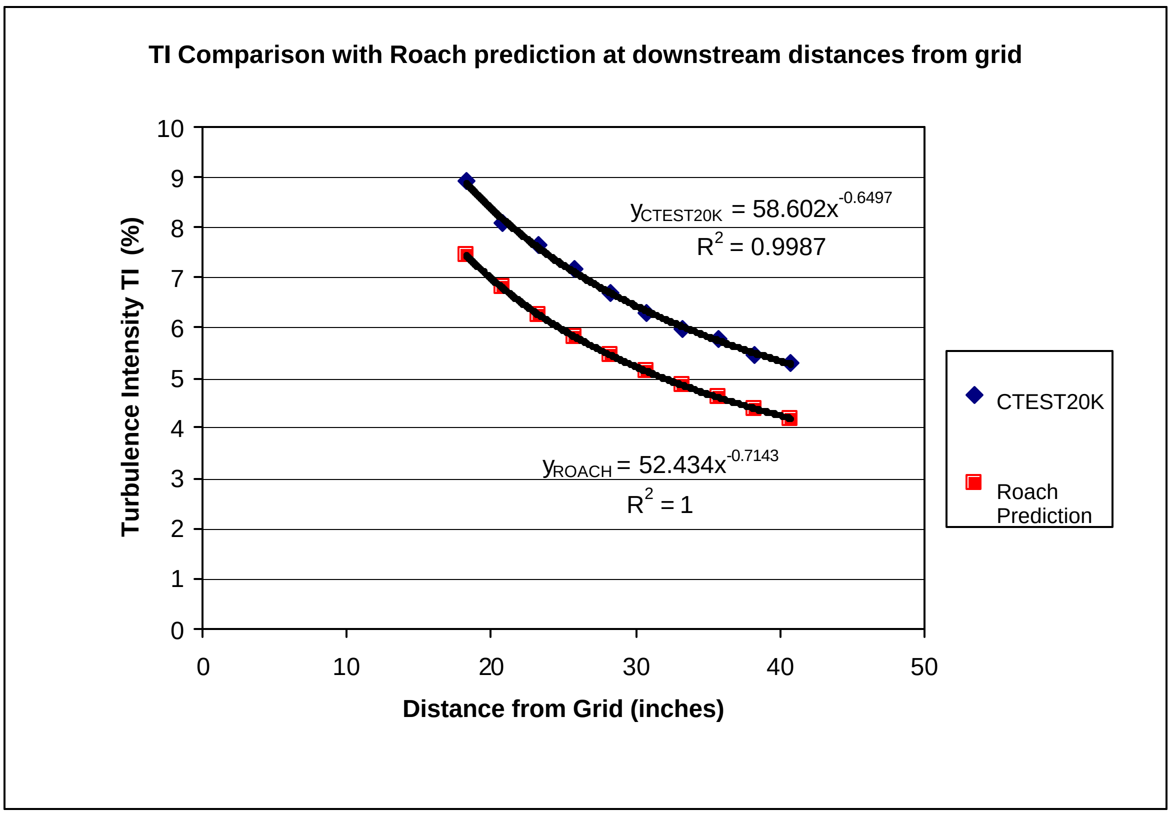

Figure 7. Turbulence Decay Plot and Equations of Trendlines

Moreover, it was noticed that for a clean tunnel with no turbulence generation grid, a dependency existed between the velocity and TI. Figure 8 indicates that a tunnel velocity of 15.298 m/s produced TI of 1.828 percent and a tunnel velocity of 15.33 m/s produced TI of 1.61 percent. The comparison between the Roach prediction and measured TI decay reveals on average a 1.23 percent difference in TI.

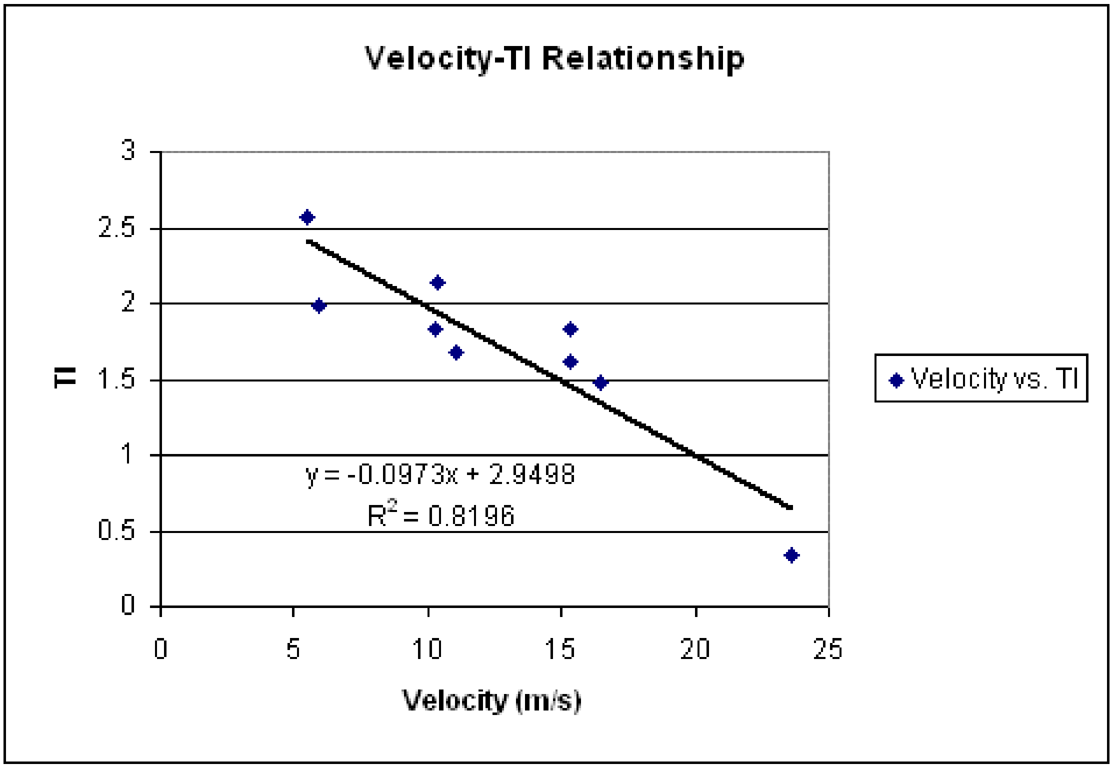

Figure 8. Velocity vs. TI Relationship at Random Velocities in Clean Tunnel

The coincidence of having the same increase in TI with and without the turbulence generation grid points to an inefficiency created somewhere in the tunnel. The equipment was checked and functioned normally, ruling out any bias error. One possible cause for a presence of TI without the turbulence grid is that an air leakage could exist within the system caused due to the current process of sealing the tunnel. Using some other method to seal the tunnel would decrease the possibility that a leakage may cause the TI to increase. Future experimentation should be performed to determine the connection between the velocity and TI relationship with no grid and the turbulence decay with the turbulence generation grid.

Velocity Versus TI Relationship

In the clean tunnel with no turbulence generation grid, a dependency on velocity and TI was noticed. Velocity and turbulence intensity data was taken for nine velocities and plotted in Fig.8.

A clean tunnel would present a velocity-TI relationship that was nearly constant; however, this graph reveals a slight velocity-TI relationship that is nearly proportional. The dependency points to flow irregularities in the wind tunnel or the presence of a possible blockage at the upstream entrance of the tunnel. This hypothesis should be explored in a follow-up experiment to further validate the flow quality of the Baylor University Wind Tunnel.

Sources of Error

A possible source of error can be reduced if the user chooses the appropriate frequency band for the micro scale, or dissipation scale. Roach[1] states that the high frequency end of the spectrum contributes the major part of the micro length scale and, thus, an insufficiently large frequency band chosen for the power spectrum (which can be used to measure the micro length scale) could create a significantly larger micro scale value than the actual value. This source of error was reduced in this experiment by (1) using the Simon et al.[2] process to find an initial estimate of the sampling rate, duration, macro, and microscales; (2) by iterating this estimation several times until a relatively consistent micro scale value was chosen; and (3) by filtering out the higher frequencies using a 20 kHz low-pass filter. A 20 kHz low-pass filter reduced possibility of choosing an incorrect macro scale; however, using a different low-pass filter might be worth investigating.

Another source of error is a systematic error related to the manual positioning method of the probe. Although this error is relatively small, this error would most likely be reduced with the use of automated positioning methods.

Conclusions and Recommendations

The first question evaluated in this experiment investigated the uniformity of the velocity and TI in the central region of the tunnel test section. Velocity and TI located in the central region of the test section, measuring 4.25 inches in height and 2.125 inches in width, were determined to be uniform within 6.5 percent of the average velocity and TI values. It is recommended that future experiments use a test section 4.25x2.125 inches located in the center of the tunnel cross-section between 30.875 and 38.5 inches downstream of the turbulence generation grid. Acquisition of data outside of this suggested area may be influenced by the increased velocity and TI fluctuations greater than 9 percent of the average values.

The second question evaluated in this experiment compared the turbulence decay downstream of the turbulence generation grid in the Baylor University Wind Tunnel with the turbulence decay predictions of Roach[1]. The measured turbulence decay of the wind tunnel had over one-percent higher TI values than Roach[1] predicted. Dependency of the TI and the velocity without the insertion of the turbulence generation grid yielded approximately a one-percent value of TI in the tunnel. The existence of TI with the absence of a grid suggests the presence of possible flow irregularities in the tunnel. The connection of the TI and velocity dependence with no turbulence generation grid and the TI decay with a grid should be investigated in a follow-up experiment.

An acceptable range of filter values between 300 Hz and 20 kHz did not create a dependency on TI. A low-pass filter setting of 10 kHz created the most appropriate frequency band for a tunnel velocity of 15 m/s. The velocity-TI dependency in the tunnel was proportional; therefore, the tunnel is not necessarily clean. Future experimentation would determine the efficiency of the tunnel and the possible causes of tunnel inefficiencies.

Four major changes for the Baylor University Wind Tunnel are recommended: a better method of positioning the probe, more time efficient method of processing the autocorrelation, faster computer processing speeds, and redesign of the turbulence generation grid. First, the manual positioning of the traverse was not a highly precise method and was tedious; it also increased the possibility of systematic error. An automated positioning system should be utilized to increase positioning accuracy and reduce the time required to manually position the probe. Second, autocorrelation processing times were excessive using the IFA-300 software. MatLab is an excellent choice of software capable of accommodating an autocorrelation program. The *Velocity Analysis* option in the IFA-300 software allows for a text file to be generated (along with the velocity and statistical files). This text file could be imported into MatLab and the autocorrelation program could be used to correlate the data. Third, faster computer processing speeds would also decrease the time required to process data. Finally, redesign of the turbulence generation grid to include grid bars on its outer edges would increase the uniformity of the velocity in the test section. The absence of outer grid bars created slightly faster velocities and TI around the edges of the tunnel cross-section because of the smaller resistance from the smooth walls. These recommendations would be beneficial to future experiments involving the Baylor University Wind Tunnel.

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