MULTI-SCALE GRID GEOMETRIES
FOR INTERNAL FLOW TURBULENCE GENERATION

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Abstract

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The results presented in this thesis describe multi-scale grid generated turbulence in an internal flow setting. Multi-scale grids offer benefits found in both passive and active grids – they can be used to generate high turbulence intensities, but still do not require any active control. Various grid geometries found in literature as well as new geometries were created. Experiments were performed at the Hessert Aerospace Lab. The test set-up consisted of flow between two flat plates separated by a distance of 8.73 cm. Single- and dual-wire hotwire probes were used to acquire time series of velocity downstream of the grids. Multi-scale grid geometries commonly found in literature were tested in the internal flow regime to determine which geometries generated high turbulence intensities that were also spatially homogeneous. New geometries were created based on these results, and finally turbulence created using two of the grids was studied extensively using a dual-wire hotwire probe.
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SYMBOLES

\( t_r \) thickness ratio
\( \sigma \) blockage ratio
\( D_f \) fractal dimension
\( n \) turbulence decay exponent
\( TI \) turbulence intensity
\( u_{rms}, u' \) R.M.S. of u-velocity
\( U_0 \) upstream centerline velocity
\( M_{eff} \) effective mesh size
\( L_{small} \) smallest geometric structure size
\( L_{large} \) distance between thickest bars
\( Re_\lambda \) turbulent Reynolds number
\( A \) miscellaneous constant
\( \bar{U} \) mean u-velocity
\( \bar{V} \) mean v-velocity
\( E \) energy
\( x \) streamwise distance
\( t \) time
\( \Lambda \) integral length scale
\( P \) production of turbulence
\( f \) frequency
CHAPTER 1

INTRODUCTION

1.1 Background

The use of multi-scale grids to produce turbulence has been a rapidly evolving area of research in recent years. Most studies focused on passively generating high free stream turbulence involve external flow applications. This paper describes the application of such a passive turbulence generation method to an internal flow.

Most practical turbulence phenomena found in nature exhibit turbulence intensities much higher than what are created in the free-stream of a typical wind tunnel, prompting the need to employ passive or active turbulence generation methods. Passive turbulence generation involves passing the free stream through a grid with known, usually homogeneous mesh geometry in order to create statistically stationary flow which varies only in the streamwise direction. After the choice of grid geometry, there is no user interaction required in generating the turbulence with a passive grid, and such a grid can generate turbulence intensities of approximately 5-7% at a streamwise distance between 1 and 2 grid heights downstream. Active grids generally involve a baseline grid with mechanical components such as flaps which can be actuated individually and can swivel on separate axes. Oscillating the flaps either randomly or in a structured manner stirs the flow in all three dimensions and creates high turbulence intensities. Active grids require user interaction for control and add a considerable amount of complexity to the system, but can generate turbulence intensities upwards of 20% at the same location downstream.
Multi-scale turbulence generation grids are passive grids with non-homogeneous mesh geometry, meaning that the bars which constitute the grid are a prescribed pattern of more than one thickness. Turbulence is thus generated at multiple scales due to the geometric features of the grid, and can resemble turbulence in naturally occurring phenomena. Because they are still passive grids, there is no user interaction after the choice of grid, and the complexity in implementation is no different than a classical homogeneous passive grid.

1.2 Literature Review

The notion of multi-scale grids stems from the idea of fractal turbulence generation grids, which were first studied extensively by Hurst and Vassilicos [1]. The authors used hot-wire anemometry to study the scaling and decay of grid generated turbulence downstream of 21 different multi-scale grids belonging to three different families of grids, as shown in Figure 1.1. Their motivation was to learn to create turbulent flow with controllable quantities such as turbulence intensity and pressure drop across the grid.

Figure 1.1. Three families of fractal grids: (left) Cross, (center) Square, (right) I [1]
The first family of grids studied by Hurst and Vassilicos was the cross grid. As seen in Figure 1.1, the cross grid consists of horizontal and vertical bars of varying thicknesses. Each grid is distinguished by the thickness ratio $t_r$, which is the ratio of the largest thickness to the smallest thickness present in the grid and the blockage ratio $\sigma$, which is the measure of the open area of the grid. A schematic of the cross grids with varying thickness ratios and blockage ratios used in their paper is shown in Figure 1.2.

![Cross grids](image)

Figure 1.2. Four cross grids tested by Hurst and Vassilicos [1]

Their experiments showed that the cross grids produce fairly homogeneous turbulence with high turbulence intensities. They also found that the turbulence decay is consistent with classical power-law decay and the principle of permanence of large
eddies, as shown in Figure 1.3. However, their work only pertained to velocities on the centerline of the tunnel for each grid. They stated that it was not possible for them to create a three-component velocity map downstream of the grids. They concluded that cross grids were highly sensitive to the thickness ratio and an effective mesh size, and that the turbulence scaled with those parameters and the pressure drop across the grid. The pressure drop and turbulence intensity could be controlled by choosing an appropriate thickness ratio and blockage ratio.

![Figure 1.3. Turbulence decay [1], cross grids: (a) streamwise component and (b) transverse component](image)

Hurst also presented a plot of the isotropy indicator in their findings. This value, representing the ratio of the streamwise to transverse velocity fluctuations, \( u'/v' \) from their findings is shown below in Figure 1.4.

![Figure 1.4. Isotropy indicator](image)
A similar study with the I- and square- families of grids resulted in much different conclusions about the grids. An important observation with I-grids was that homogeneity increased with increasing fractal dimension, and there was a threshold fractal dimension ($D_f = 2$) above which production increased with the thickness ratio instead of the mean velocity gradient. The turbulence produced was less homogeneous than either the classical or cross grids, and its decay followed a power law fit, but as per the authors it could not fully be understood without more detailed studies of the large-scale and small-scale isotropy. For the square fractal grids, which were all space-filling ($D_f = 2$), the turbulence characteristics were the most non-classical. The authors found that downstream of the square fractal grid, the turbulence intensities actually built up until a critical streamwise distance, after which the decay did not
follow a power-law fit, but rather an exponential fit. This led to the conclusion that the principle of the permanence of large eddies did not hold in the case of space-filling square grids.

Many papers have since expanded on the work of Hurst and Vassilicos. Krogstad and Davidson [2] chose to study the cross grid in further detail. They stated that since the large transverse gradients of mean velocity immediately downstream of a multi-scale grid led to a large amount of turbulence energy production, there was a transient region of high inhomogeneities in the mean and fluctuating velocity components. After this region, there was no significant difference in the decay characteristics such as $\text{Re}_\lambda$ and the decay exponent $n$ between the cross grids and the classical prediction of Saffman turbulence, which predicts a value of $n = 6/5$ for the decay exponent. There are several papers which focus on studying the square fractal grid due to its highly non-classical nature.

Laizet and Vassilicos [3] present a brief history of fractal physics and provide preliminary DNS work modeling fractal turbulence generation grids. In the paper they provide several reasons why the study of multi-scale turbulence is important and where it can be utilized in research. They mention how trees rely on a fractal shape to maximize photosynthesis, and how lungs rely on a fractal shape to maximize oxygen delivery to the bloodstream. The authors discuss the multiscale range of turbulent eddy excitations in the atmospheric boundary layer and the impossibility of resolving such a wide range of eddy scales in a wind tunnel setting. In fluid flow problems such as turbulent flames and chemical reactors, the chemistry gives rise to additional inherent scales which are difficult to create passively in a wind tunnel. They mention that multi-scale grids could additionally be used in flow applications related to the atmosphere-ocean interaction, atmosphere-biosphere interaction, studies with ocean floor topography, pollutant dispersal, trees, coral reefs, and respiratory systems as
well as other applications such as mixers, ventilation, combustors, burners, and airbrakes. They discuss how the work of Hurst and Vassilicos could be used to design a fractal grid with a high turbulence intensity and low pressure drop, as needed for an energy-efficient mixer, or one with low turbulence intensity and high pressure drop, as needed in airbrakes. The DNS results presented in the paper show agreement in turbulence intensity decay with the Hurst results after a certain streamwise distance.

1.3 Objectives

Both Krogstad and Hurst mention the need to extensively study the role of inhomogeneities in the mean and fluctuating component of velocity downstream of the multi-scale grid. Understanding the relationship between turbulence intensity and homogeneity can be used for many applications, such as creating a multi-scale grid for efficient fuel-air mixing in combustors. In internal flow applications such as gas-turbine engines, multi-scale grids can be used in a laboratory setting to simulate flows throughout the engine, and especially at the exit of combustor going into the first stage turbine nozzle where turbulence intensities are extremely high. Laizet mentions how the expenses of pumping oil through pipelines are directly related to the skin friction drag caused by high turbulence intensity flow and that a 10% reduction in drag could save billions of dollars in shipping worldwide. Being able to create a well-understood multi-scale grid in a lab setting would be an important asset in understanding such specific turbulent flows found in nature.

The results of this study give an insight into the relationship between turbulence intensity and turbulence homogeneity. A three-dimensional turbulent flow-field behind a variety of multi-scale grids was studied using hot-wire anemometry. Variations of the cross grid were studied in more detail, and finally the cross and classical grids were studied extensively using a two-wire hotwire probe.
CHAPTER 2

EXPERIMENTAL METHODS

2.1 Overview

Turbulence grid tests were performed at the Hessert Laboratory for Aerospace Research at the University of Notre Dame to study turbulence downstream of multi-scale grids. A test section was designed and manufactured in the Machine Shop at Hessert. The grids were designed on ProEngineer and fabricated out of basswood using a precision laser cutter. Hot-wire probes manufactured by Dantec were used to acquire time series of streamwise velocity.

2.2 Wind Tunnel and Test Section

A Class 2 model centrifugal blower manufactured by New York Blowers was used as the prime mover of air in the wind tunnel. The blower had a design point of 10,000 CFM at an inlet temperature of 296 K, and a pressure rise of 2.3 kPa. The 0.91 m x 0.61 m exit of the blower was expanded to a 0.91 m x 0.91 m section using a straight-wall aluminum diffuser, and the symmetrical section was then extended 1.22 m in length and contained 4 screens and a honeycomb for flow conditioning, as seen in Figure [2.1]. The test section shown in Figure [2.2] was clamped onto the end of the symmetric wind tunnel section with a combination of spring clamps and C-clamps.
Figure 2.1. Schematic of Wind Tunnel

The test section was designed to study flow between two flat plates separated by a distance of 8.73 cm. This channel height was also referred to as the span. An aspect ratio of 8:1 was chosen for the entire test section to avoid any sidewall effects, leading to the test section dimension of 69.9 cm x 8.73 cm. A hole the size of the test section was made in a plywood sheet placed over the blower exit. Half sections PVC piping were connected to the back of the sheet in a picture-frame fashion to guide the flow into the test section area. Metal plates were bolted onto the front face of the plywood using angle brackets. These metal plates had slots 0.32 cm x 0.32 cm x 69.9 cm where the turbulence generation grids could be placed. Plexiglass plates were mounted to the sides of the metal plates to create transparent sidewalls. A ProE model of the set-up without the sidewall PVC half-sections can be seen below in Figure 2.2.
2.3 Grid Design and Manufacture

The turbulence generation grid geometries were designed using ProEngineer. The grids were constructed out of 0.3175 cm thick basswood sheets from National Balsa. Basswood was chosen as it is harder and sturdier than balsa wood, but is still soft enough to make precision cuts with. The design from ProEngineer was then cut out of the wood using the VLS 6.60 precision laser cutter manufactured by Universal Laser Systems. A schematic of the turbulence grid placed in the test section is shown in Figure 2.3.
2.4 Hotwire and Data Acquisition

A Dantec Single-Wire Miniature and Dantec Miniature X-wire straight probes were used to acquire the data. All sensors had wires of 5 \( \mu \)m diameter, 1.25 mm length, an approximate resistance of 3.5 \( \Omega \) and were made out of platinum-coated tungsten. The single-wire and X-wire probes were tuned in airflow with a velocity of about 20 m/s. Both probes were calibrated by running the tunnel at 8 different velocities from 0 to 25 m/s. King’s Law was used to acquire velocities from voltages for both types of probes, and the sum and difference calibration method outlined in Bruun [4] was used to obtain two components of velocity with the X-wire. In using the sum-and-difference approach, the yaw function \( f(\alpha) = (\cos^2 \alpha + k^2 \sin^2 \alpha)^{\frac{1}{2}} \) was used. A sampling time of 10 s was chosen for all the tests after a convergence test. The frequency roll-off of the energy spectra of turbulence behind the grids was typically around 30-35 kHz, and thus 80 kHz was chosen as the sampling frequency.
to satisfy the Nyquist criterion. A free-stream velocity of approximately 14 m/s was chosen for all the tests, leading to a Reynolds number based on the channel height of roughly 75,000. A 0-3.74 kPa Setra Model 239 differential pressure transducer with a Pitot-Static tube was used to acquire the centerline velocity upstream of the grid. The differential pressure samples were taken for 2 s at a frequency of 1.5 kHz after similar convergence tests.

All tests were performed at Hessert Aerospace Lab. Data was acquired using a National Instruments USB-6210, which is a 16-bit, 250 kHz data acquisition card. The Data Acquisition Toolbox in MATLAB was used to operate the DAQ and write the data to memory. A three-axis traverse system using Applied Motion Systems stepper motor controllers was used to traverse the single- and dual-wire probes downstream of the grid. The axis was also controlled through MATLAB using ASCII commands.
CHAPTER 3

BRIEF STUDY OF CLASSICAL, CROSS, SQUARE AND I GRIDS

The cross, square and I families of grids were adapted to fit into the test section. All the grids had a thickness ratio, the ratio of thickest to thinnest bar of 4 and only had bars of two thicknesses: 0.635 cm and 0.159 cm. The general shape of the grids as well as the classical grid can be seen in Figure 4.12.

Figure 3.1. First grids created using laser cutter: (a) Classical, (b) Cross, (c) Square, (d) I (right)

A 200-point (10 x-direction x 20 z-direction) single hotwire survey was performed at multiple axial locations downstream of each of the grid. This initial set of tests was primarily meant to give a qualitative understanding of the flow, turbulence decay and turbulence homogeneity behind each type of grid in an internal flow setting.
The spatially averaged turbulence intensity as a function of the streamwise distance for each grid is plotted in Figure 3.2. Consistent with data found in literature, at any streamwise distance, the cross grid generated the highest turbulence intensity. All four grids seemed to follow some sort of power-law turbulence intensity decay. The non-classical behavior of the square grid turbulence intensity increasing and then exponentially decreasing reported in literature was not observed, but that was most likely due to the very limited sample size of four data points. As expected, the classical homogeneous grid generated a turbulence intensity of about 5% at a streamwise distance equal to the channel height, or span.

![Figure 3.2. Turbulence intensity decay of first grids tested](image)

Reason to eliminate square and I-grids: To study the inhomogeneity of turbulence
behind the multi-scale grids, a new variable called non-uniformity was defined as the root mean square of the turbulence intensity as such:

\[ Non\ Uniformity = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (TI_i - \overline{TI})^2} \]  

(3.1)

This variable, calculated as a percentage, is a measure of the spatial inhomogeneity in the two-dimensional turbulence intensity map at any streamwise location. This measure of inhomogeneity can be plotted against the mean spatial turbulence intensity to help understand the balance between the two quantities. Typically, data points obtained at a streamwise distance far away from the grid would be represented towards the origin of the plot, since far away from the grid the turbulence assumedly decays to a low turbulence intensity value and has low inhomogeneity. Data points obtained very close to the grid would appear in the opposite corner of the plot, since the velocity map immediately downstream of the grid is highly inhomogeneous and the wide range of turbulence scales also causes the high turbulence intensity. This concept was captured accurately in Figure 3.3, which shows the non-uniformity associated with each of the four grids plotted against the mean spatial turbulence intensity.
As expected, the classical grid was the most homogeneous but also did not generate high turbulence intensities. The square- and I- grids generated high turbulence intensity flows, but the inhomogeneities were generally upwards of 20%. The grids showed a linear relationship between the turbulence intensity and inhomogeneity, and the cross grid had inhomogeneities under 10% at all streamwise distances tested.

Most turbulence models make certain assumptions when dealing with high turbulence intensity flows, and one of them is usually that the flow is homogeneous. There is not an easy way to model inhomogeneities such as 20%, as seen with the square- and I-grids. For that reason, those grid geometries were excluded from further studies. Since the cross grid provided a good balance between high and fairly homogeneous turbulence intensities, other variations of this grid were created and tested using the

Figure 3.3. Turbulence intensity vs. spatial inhomogeneity for initial grids
same bi-scale nature of the grid. Four new grids were created that maintained the baseline cross-pattern of the cross grid and contained only two geometric scales, and all had a solidity of roughly 0.47. These can be seen in Figure 3.4.

Figure 3.4. Variations of Cross Grid created: (a) Diamond, (b) Blend, (c) Fine Cross, (d) TR3 Cross

The diamond grid and blend grid both incorporated the same bar thicknesses and thickness ratio as the cross grid. The fine cross grid had the same thickness ratio as the cross grid, but the bar sizes were 0.508 cm and 0.127 cm. The TR3 cross grid was named so because it had a thickness ratio of 3, with bar sizes of 0.381 cm and 0.127 cm. Two-dimensional 200-point surveys with a single wire hotwire were taken at multiple streamwise distances, and the resulting turbulence intensity decay is shown in Figure 3.5.
As seen in Figure 3.5, at any streamwise distance the cross grid still generated the highest turbulence intensity. The diamond and blend grids, which had the same thickness ratio and bar thicknesses as the cross grid produced comparable levels of turbulence. It was interesting to find that the turbulence intensity was not governed by the thickness ratio only, since the cross and fine cross grids had the same thickness ratio, but produced different turbulence intensity levels at the same streamwise distance. This led to a conclusion that the thickness of the bars also plays a role in generating a high turbulence intensity flow.

The plot of turbulence intensity as a function of the inhomogeneity was plotted for these new grids in Figure 3.6. It can be seen that the cross, diamond and blend grids all showed similar trends, most likely due to the very similar geometric features.
For the diamond and blend grids, having vorticity vectors aligned with the diagonal caused a slight reduction in turbulence intensity due to the decreased magnitude of the cross-stream velocity fluctuations. The most interesting feature of the plot was that contrary to intuition, the fine cross grid with the same thickness ratio but thinner bars resulted in a less homogeneous turbulence intensity field, and the TR3 cross grid with the lower thickness ratio led to even more inhomogeneities and lower turbulence intensities. It is surprising that more geometric homogeneity did not translate to turbulence intensity homogeneity as it did with the classical grid.

![Figure 3.6. Turbulence intensity vs. spatial inhomogeneity for variations of cross grids](image)

Thus far the spatial mean of turbulence intensity had been plotted as a function
of the physical streamwise distance downstream of the grid. Studies were done to find a variable to collapse the data from the various grids. The effective mesh size defined by Hurst was calculated for all the grids and considered as a scaling parameter in Figure 3.7. A slight collapse in the turbulence intensity decay of the multi-scale grids was observed, but the classical grid data did not collapse well onto the curve.

![Figure 3.7. Turbulence intensity decay, scaled using $M_{eff}$](image)

The next logical choice for a length scale to collapse the data was the smallest geometric structure in the grid, so for example the hole diameter for the classical grid, or the smallest square edge of the cross grids, and the triangle base of the blend and diamond grids. The turbulence intensity decay was re-plotted using this length scale in Figure 3.8. From this plot, it was clear that the turbulence did not decay
according to the smallest geometric scale of the grid.

![Figure 3.8. Turbulence intensity decay, scaled using $L_{small}$](image)

Since the smallest geometric scale did not collapse the data, the next choice of length scale was the largest geometric scale in the grid. Since the classical grid consisted of evenly spaced circular holes, this length scale was the same as in Figure 4.2.1. For the other grids, this choice of length scale corresponded to the distance between the thickest bars of the grid. Using this length scale, which was called $L_{large}$, the turbulence intensity decay was plotted in Figure 3.9 and seemed to collapse the data the best compared to Figures 3.7 and 3.8.
The Reynolds number based on the Taylor microscale was calculated for the various grids and plotted as function of the $L_{\text{large}}$ to verify that the data collapsed using the choice of length scale. As seen in Figure 3.10, the choice of length scale collapses the turbulent Reynolds number very well.
Figure 3.10. Streamwise Turbulent Reynolds Number
It was determined that the cross grid was capable of generating high turbulence intensities with fairly low inhomogeneities. To fully understand the flow physics downstream of this grid, an extensive X-wire survey was taken at 5 streamwise locations downstream of the grid: 2.54 cm, 6.35 cm, 10.16 cm, 17.78 cm and 25.4 cm. At each location, the 8.73 cm x 8.73 cm area shown in Figure 2.3 was traversed using 25 points in the y-direction and 40 points in the z-direction, leading to a 1000-point traverse. An X-wire traverse was also taken downstream of the classical grid for comparison, but due to the inherent geometrical homogeneity of the grid this test matrix was only a 20 x 40 point survey. The kinetic energy decay of both the cross and classical grid were first plotted against the streamwise distance normalized by $L_{large}$ as per the following relation.

$$\left( \frac{u'}{U_0} \right)^2 \propto A \left( \frac{x}{L_{large}} \right)^{-n} \quad (4.1)$$

The values of $L_{large}$ were 2.35 cm and 0.8 cm for the cross and classical grids respectively. The turbulence decay is plotted in Figure 4.1.
Figure 4.1. Decay of turbulence downstream of cross and classical grids

Again, it was seen that the scaling variable $L_{large}$ successfully collapsed the turbulence data. It was found that the decay exponent $n$ for the cross grid was 1.301, and the decay exponent for the classical grid was 1.582.

4.1 Classical Grid

4.1.1 Velocity Contours

The U- and V- components of velocity calculated at the five streamwise locations for the classical grid are shown in Figures 4.2 - 4.6. It can be seen that close to the grid, the flow is highly influenced by the geometry of the grid. The geometric
dependence of velocity quickly diminishes for the further downstream traverses, and as seen in Figure 4.6(a), the velocity profile mostly resembles flow between two flat plate with boundary layers along the walls. The V-velocity is also very dependent on geometry close to the grid, but becomes much less predictable further downstream. Each plot has a different color bar based on the minimum and maximum value. This was done to better understand some flow physics, as will be clear further in the document.

Figure 4.2. Velocity Contours at $x = 2.54$ cm downstream of grid
Figure 4.3. Velocity Contours at \( x = 6.35 \) cm downstream of grid

(a) Contours of \( \frac{U}{U_0} \)
(b) Contours of \( \frac{V}{U_0} \)

Figure 4.4. Velocity Contours at \( x = 10.16 \) cm downstream of grid

(a) Contours of \( \frac{\overline{U}}{U_0} \)
(b) Contours of \( \frac{\overline{V}}{U_0} \)
Figure 4.5. Velocity Contours at $x = 17.78$ cm downstream of grid

Figure 4.6. Velocity Contours at $x = 25.4$ cm downstream of grid
4.1.2 Turbulence Intensity Contours

The U- and V-components of turbulence intensity calculated at the five streamwise locations for the cross grid are shown in Figures 4.7 - 4.11. It can again be seen that the grid geometry directly influences the turbulent fluctuations of both components of velocity. There is a slight improvement in TI$_u$ homogeneity between $x = 2.54$ cm and $x = 6.35$ cm, but there is a significant jump in homogeneity between $x = 6.35$ cm and $x = 10.16$ cm. At some distance between 6.35 cm and 10.16 cm downstream of the grid, the turbulence intensities become very homogeneous in both the u- and v-directions, but the magnitude of turbulence intensity also decreases. Evident in the $x = 17.78$ cm and especially in the $x = 25.4$ cm case, the turbulence intensities are extremely homogeneous.

Figure 4.7. Turbulence Intensity Contours at $x = 2.54$ cm downstream of grid
Figure 4.8. Turbulence Intensity Contours at $x = 6.35$ cm downstream of grid

Figure 4.9. Turbulence Intensity Contours at $x = 10.16$ cm downstream of grid
Figure 4.10. Turbulence Intensity Contours at x = 17.78 cm downstream of grid

Figure 4.11. Turbulence Intensity Contours at x = 25.4 cm downstream of grid
4.1.3 Integral Length Scales

There are two equivalent methods of calculating the integral length scale from the velocity time series. The integral length scale can be found by taking the integral of the autocorrelation function of the velocity fluctuation. This method could be used very easily with the classical grid because the fairly homogeneous turbulence resulted in a smooth autocorrelation function usually with zero crossings. When the turbulence was created using the multi-scale grids, the autocorrelation function showed kurtosis effects due to the higher turbulence intensities. This made the integral length scale incorrectly dependent on the limits of integration of the autocorrelation function. Thus, another method of finding the integral length scale as described by Hinze [5] was used to calculate the U- and V- length scales.

The calculation method begins with the idea that the spectrum of turbulence describes the relationship between the energy content of the fluid to the frequency. Thus, in the band of frequencies ranging from \( n \) to \( n + dn \), the function \( E_1 \) can be defined as such that \( E_1(n) \, dn \) is the contribution of the frequencies to \( u'^2 \), otherwise expressed as:

\[
\bar{u'^2} = \int_{0}^{\infty} E_1(n) \, dn
\] (4.2)

Defining \( f(x) \) as the streamwise correlation function, Hinze showed that using Fourier transforms,

\[
f(x) = \frac{1}{u'^2} \int_{0}^{\infty} E_1(n) \cos \left( \frac{2\pi nx}{U} \right) \, dn
\] (4.3)

Using the inverse transform relation,

\[
E_1(n) = \frac{4u'^2}{U} \int_{0}^{\infty} f(x) \cos \left( \frac{2\pi nx}{U} \right) \, dx
\] (4.4)
From Equation 4.4 and using Taylor’s Frozen field hypothesis, that is \( x = \bar{u} \cdot t \), the following equation can be derived, where the right hand side of the equation is the definition of the integral length scale \( \Lambda_f \equiv \int_0^\infty f(x) \, dx \).

\[
\lim_{n \to 0} \left[ \frac{\bar{U}}{4u'^2} E_1(n) \right] = \int_0^\infty f(x) \, dx \quad (4.5)
\]

Thus, in the limit of \( E_1 \) as \( n \to 0 \),

\[
\Lambda_f = \frac{\bar{U}E_1(0)}{4u'^2} \quad (4.6)
\]

This method of calculating the integral length scale has been be validated using experimental data. First shown in Hinze, when the turbulence spectrum is collapsed using Equation 4.6 the value of \( E_1(0) \) converges to a value of 4, as calculated in Equation 4.6. Working backwards, if the value of \( E_1(0) \) is known as is the case with hot-wire measurements, the integral length scale can be calculated using Equation 4.6.
Figure 4.12. The spectral function $E_1(n)$ for $u'$ fluctuations downstream of a grid. From Favre et al. (1953)

This method could also be applied to the transverse integral length scale using the fluctuating component of the transverse velocity. Using this method, the U- and V-integral length scale contours normalized by $L_{\text{large}}$ were calculated for the grids at all the streamwise locations. These are shown in Figures 4.13 to 4.17. It was seen that even very close to the grid, the integral length scales in both directions had fairly homogeneous contours with the major aberrations near the endwalls. Similar to the turbulence intensity contours, at a streamwise distance between 6.35 cm and 10.16 cm downstream of the grid, the integral length scale contours became very homogeneous, with almost all of the inhomogeneity arising due to the boundary
layers. Once homogeneous, the U-integral length scale was roughly 60% of $L_{\text{large}}$.

Figure 4.13. Integral Length Scale Contours at $x = 2.54$ cm downstream of grid
Figure 4.14. Integral Length Scale Contours at $x = 6.35$ cm downstream of grid

Figure 4.15. Integral Length Scale Contours at $x = 10.16$ cm downstream of grid
Figure 4.16. Integral Length Scale Contours at $x = 17.78$ cm downstream of grid

Figure 4.17. Integral Length Scale Contours at $x = 25.4$ cm downstream of grid
It can be shown from the definition of autocorrelation functions that in homogeneous, isotropic turbulence the transverse integral length scale is equal to half of the longitudinal length scale. To determine whether isotropic turbulence was being produced as expected, contours of $\Lambda_u/\Lambda_v$ were plotted at all the streamwise locations, meaning that a value of 2 on this plot would indicate isotropic turbulence.
It was seen that close to the grid, the ratio of the transverse to longitudinal length...
scale was about 1.5-1.6. This ratio continued to build with streamwise distance, and at a streamwise distance of 25.4 cm, the ratio was 2 roughly everywhere except the boundary layers, indicating isotropic turbulence as expected.

4.1.4 Isotropy

Contours of the isotropy indicator $u'/v'$ were also plotted at the streamwise distance to provide a comparison to the Hurst findings. According to the Hurst paper, the isotropy indicator takes a value of approximately 1.2 for the classical grid and between 1.2 and 1.3 for the cross grid. In both cases, the value is higher towards the endwalls due to the fact that $\bar{V} = 0$, and the transverse velocity fluctuations are small compared to streamwise velocity fluctuations. The resulting contours are shown in Figure 4.19. It was seen that for the classical grid, the isotropy indicator matched somewhat closely to the results from Hurst. After the flow became very homogeneous somewhere between 6.35 cm and 10.16 cm downstream of the grid, the value of $u'/v'$ was generally around 1.3 for most of the flow and about 1.7 in the boundary layer.
Figure 4.19. $u'/v'$ downstream of classical grid
4.1.5 Reynolds Stress

Contours of Reynolds stress normalized by $U_0^2$ were computed downstream of the grid and are plotted in Figure 4.20. It was seen that the Reynolds stress was the highest downstream of the holes in the grid. At 6.35 cm downstream of the grid, the Reynolds stress contours began to form horizontal bands at the location of the hole bands, and began to decay in magnitude between 6.35 cm and 10.16 cm downstream of the grid. As previously mentioned, the turbulence was pretty homogeneous at the 17.78 cm and 25.4 cm downstream locations, and this was reflected in the low Reynolds stresses, indicating that turbulence was not being produced.
Figure 4.20. $\overline{u'v'}/U_0^2$ downstream of classical grid
4.1.6 Production

The production term \( P = -\overline{u'v'} \cdot (d\bar{U}/dy) \) was calculated for the classical grid at the 5 downstream locations. The contours or P normalized by \((U_0)^3/\Lambda_u\) have been plotted in Figure 4.21. The turbulence is produced at the grid and is heavily prevalent close to the grid. For the further downstream locations, the turbulence production decays rapidly and there is close to no production at the 17.78 cm and 25.4 cm downstream locations, as expected in homogeneous grid generated turbulence.
Figure 4.21. $P/((U_0)^3/\Lambda_u)$ downstream of classical grid
4.2 Cross Grid

4.2.1 Velocity Contours

The U- and V- components of velocity calculated at the five streamwise locations for the cross grid are shown in Figures 4.22 - 4.26. It can be seen that the U-velocity contours are extremely dependent on the geometry of the thick bars of the grid. Figure 4.22(a) clearly shows that the flow is retarded the most by the thick bars and flows through the open spaces between the thick bars, which we have previously defined as $L_{\text{large}}$. This is in perfect agreement with the notion that the turbulence scales best with $L_{\text{large}}$, as seen in Figure .

![Figure 4.22](image.png)

(a) Contours of $U/U_0$  (b) Contours of $V/U_0$

Figure 4.22. Velocity Contours at $x = 2.54$ cm downstream of grid
Figure 4.23. Velocity Contours at x = 6.35 cm downstream of grid

Figure 4.24. Velocity Contours at x = 10.16 cm downstream of grid
Figure 4.25. Velocity Contours at $x = 17.78$ cm downstream of grid

Figure 4.26. Velocity Contours at $x = 25.4$ cm downstream of grid

The U-velocity contours are certainly influenced by the grid geometry for the first
three streamwise locations tested, but at some distance between 10.16 cm and 17.78 cm, the contours become fairly homogeneous. It is crucial to note that the colorbars are very different for all the plots. This was done intentionally to capture all of the flow physics. At the furthest streamwise distance, the U-velocity field resembles that of a flow between flat plates. The V-velocity contours were found to be slightly offset from the U-velocity contours, implying that the largest transverse velocities were downstream of the thick bars. Again, the influence of the grid geometry on the transverse velocity contours diminished between 10.16 cm and 17.78 cm downstream of the grid.

4.2.2 Turbulence Intensity Contours

The U- and V- components of turbulence intensity calculated at the five streamwise locations for the cross grid are shown in Figures 4.27 to 4.31.

Figure 4.27. Turbulence Intensity Contours at x = 2.54 cm downstream of grid
Figure 4.28. Turbulence Intensity Contours at $x = 6.35$ cm downstream of grid

Figure 4.29. Turbulence Intensity Contours at $x = 10.16$ cm downstream of grid
Figure 4.30. Turbulence Intensity Contours at $x = 17.78$ cm downstream of grid

Figure 4.31. Turbulence Intensity Contours at $x = 25.4$ cm downstream of grid
It was seen that the turbulence intensity contours are also clearly affected by the grid geometry. Close to the grid, the regions of high turbulence intensity form rings within the space enclosed by the thick bars. At a distance of 10.16 cm downstream of the grid, the streamwise turbulence intensity contours start to become homogeneous, but the transverse turbulence intensity contours form distinct bands corresponding with the vertical columns inherent to the grid. At 17.78 cm downstream of the grid, the \( TI_u \) contours are more homogeneous, but the \( TI_v \) contours are very homogeneous, with the only deviations near the wall. At the furthest downstream location tested and again noting the color bars, it was seen that the contours of \( TI_u \) were only slightly influenced by the grid geometry, while the \( TI_v \) contours were very homogeneous.

4.2.3 Integral Length Scales

Using the aforementioned method, the U- and V- integral length scale contours normalized by \( L_{\text{large}} \) were calculated for the cross grid at all the streamwise locations. These are shown in Figures 4.32 to 4.36. It was found that close to the grid, the locations of the largest turbulence scale was influenced by \( L_{\text{large}} \) in that the region enclosed by the thick bars contained the highest magnitudes of integral length scale. Both integral length scales continued to increase and became fairly homogeneous with increasing downstream location. At the furthest downstream distance, the integral length scale was about 50% of \( L_{\text{large}} \), comparable to approximately 60% for the classical grid.
Figure 4.32. Integral Length Scale Contours at $x = 2.54$ cm downstream of grid

Figure 4.33. Integral Length Scale Contours at $x = 6.35$ cm downstream of grid
Figure 4.34. Integral Length Scale Contours at $x = 10.16$ cm downstream of grid

(a) Contours of $\Lambda_u$

(b) Contours of $\Lambda_v$

Figure 4.35. Integral Length Scale Contours at $x = 17.78$ cm downstream of grid

(a) Contours of $\Lambda_u$

(b) Contours of $\Lambda_v$
Figure 4.36. Integral Length Scale Contours at \( x = 25.4 \) cm downstream of grid

Contours of \( \Lambda_u/\Lambda_v \) were plotted at all the streamwise location, again with the idea that a value of 2 for this ratio indicated homogeneous, isotropic turbulence. As seen in Figure 4.37, the ratio \( \Lambda_u/\Lambda_v \) took values under 2 very close to the grid, but quickly converged to a value of roughly 2 with increasing downstream distance. Even at the furthest streamwise distance tested, the average value of \( \Lambda_u/\Lambda_v \) was slightly above 2, indicating that the flow was fairly isotropic, but not entirely.
Figure 4.37. $\Lambda_u/\Lambda_v$ downstream of cross grid
4.2.4 Isotropy

Contours of the isotropy indicator $u'/v'$ were also plotted for the cross grid. Like previously mentioned, according to the Hurst paper, the isotropy indicator takes a value of approximately 1.2 for the classical grid and between 1.2 and 1.3 for the cross grid. For this internal flow application, it was found that once the flow was determined to be homogeneous, the isotropy indicator was closer to 1.5 for most of the data points and about 2 at the endwalls.
Figure 4.38. $u'/v'$ downstream of cross grid.
4.2.5 Reynolds Stress

Contours of normalized Reynolds stress were computed downstream of the grid and are plotted in Figure 4.39. This figure also helped explain why the turbulence intensities were higher for the multi-scale grids compared to the classical grid. For the classical grid, the Reynolds stresses formed horizontal bands which eventually decayed. For the multi-scale cross grid, the Reynolds stress bands persisted even at the far downstream locations, only to decay by an order of magnitude between 17.78 cm and 25.4 cm downstream of the grid. This implied that production would be close to zero only after $x = 17.78$ cm.
Figure 4.39. $\overline{u'v'}/U_0^2$ downstream of cross grid
4.2.6 Production

The production term \( P = -\overline{u'v'} \cdot (d\overline{U}/dy) \) was calculated for the cross grid at the 5 downstream locations. The normalized contours have been plotted in Figure 4.40. It was seen that most of the turbulence was produced in two distinct horizontal bands at roughly the 20% and 65% span locations. The production term decayed with streamwise distance as expected, but only reached values close to zero after 17.78 cm downstream of the grid.
Figure 4.40. $P/((U_0)^3/\Lambda_u)$ downstream of cross grid
4.3 Energy Spectra

The energy spectrum of turbulence was calculated from the fluctuating component of streamwise velocity downstream of the grids at the centerline. The spectra were first plotted at a fixed streamwise location for the cross, diamond, blend and classical grids. These are shown in Figure 4.41. The spectra showed fairly predictable characteristics not unusual to typical turbulence spectra found in literature.

![Energy spectra of classical and multi-scale grids at same physical location](image)

Figure 4.41. Energy spectra of classical and multi-scale grids at same physical location
However, to understand the physics better it was necessary to study the spectra for the various grids at the same normalized streamwise location. This was done by plotting the spectra for a value of $x/L_{\text{large}} \approx 8$ for the grids. This is shown in Figure 4.42.

![Figure 4.42. Energy spectra at normalized streamwise location](image)

Figure 4.42 was very informative, as it further ascertained the notion of using $L_{\text{large}}$ as a scaling variable, since the spectra seemed to collapse together pretty well. The plot also showed that the multi-scale grids exhibited a distinct $-5/3$ slope region as derived from Kolmogorov’s second similarity hypothesis, while the classical grid did not show a clearly discernible $-5/3$ region in the spectra when used in the internal flow setting. The spectra of the cross and classical grids were further studied using a
larger windowing size in the data processing and are plotted in Figure 4.43.

Figure 4.43 shows that the multi-scale cross grid generates turbulence of a well-defined spectrum compared to the classical grid in the internal flow regime. For the cross grid, there was clearly a region of high energy containing large eddies, an inertial subrange that spanned nearly a decade of frequencies, and a rapid decline of energy as it was transferred to the smallest scales of turbulence. In contrast, the classical grid did not show a clear inertial subrange of turbulent motions.

The two-component coherence spectrum was plotted for the cross and classical grids at the same normalized streamwise distance of $x/L_{\text{large}} \approx 8$ and is shown in
Figure 4.44. It was seen that classical grid had an anisotropy peak at a normalized frequency of about 5, while the cross grid had an anisotropy peak at a normalized frequency of approximately 15.
Several conclusions could be drawn from the research presented in this document. The study stemmed from the work of Hurst and Vassilicos. It expanded a concept mentioned throughout literature that there is a need to study the role of inhomogeneities in the turbulence characteristics downstream of multi-scale grid generated turbulence. A primary objective of the study was to find a grid geometry to maximize the magnitude of turbulence intensity while minimizing the inhomogeneity in this same quantity. The work showed that there is clearly a relationship between the magnitude of turbulence intensity created by the grids, and the level of homogeneity in this fluctuating component of velocity.

The square grid has become a topic of much detailed study within the turbulence community due to its highly non-classical behavior. It has been found that downstream of the square grid, the turbulence intensity builds up until a critical distance, after which it begins to decay. Although such a trend was not found in this study, it can mostly be attested to the dearth of data points. It was found that for almost all downstream distances tested, the turbulence intensity had spatial inhomogeneities near or above 20%. For the objective of the study, these were deemed to be too high, and thus the square grid was not studied in detail.

Turbulence generated with the I-grid proved to be the furthest from the objective of the study. The turbulence intensity of the flow at any streamwise distance was greater than the classical grid, however, due to the presence of a thick I-shaped bar
in the center of the traverse area, the inhomogeneities in turbulence intensity were very high and the grid was not studied in detail.

The diamond and blend grids were the closest to the cross grid in terms of the relationship between the turbulence intensity and spatial inhomogeneity. The grids were designed with the idea that the presence of diagonal elements in the grid would result in vorticity vectors aligned in more than two directions immediately downstream of the grid, perhaps resulting in a more homogeneous flow. It was found that this resulted in lower turbulence intensities than the cross grid, as momentum transport was aided by the diagonal vorticity vectors and thus the fluctuating components of velocity were not as high as the cross grid.

The cross grid provided the best balance between creating a high turbulence intensity flow that was also spatially homogeneous. An important finding was that even in an internal flow setting, the grid displayed power-law turbulence intensity decay. Detailed study of the cross grid revealed that the velocity and turbulence intensity are highly influenced by the grid geometry immediately downstream of the grid. The geometric influence appeared to be especially prevalent for the first three downstream locations tested. The ratio of integral length scales $\Lambda_u/\Lambda_v$ was approximately equal to 2 after 17.78 cm downstream of the grid.

The classical grid design with an evenly spaced hole pattern produced turbulence intensities on the order of 5%, as expected. There was a clear power-law turbulence decay, and the turbulence intensity was fairly homogeneous very close downstream of the grid. The geometric influence on the turbulence was not quite as drastic as the cross grid, and only persisted for the first two streamwise distances tested. Both the isotropy indicator and the ratio of integral length scales showed that homogeneous, isotropic turbulence was produced after a distance of 6.35 cm.
It was found that the distance between the thickest bars of the grid was the best scaling parameter for the turbulence characteristics such as turbulence intensity and Reynolds number. Another important result of this study was that the multi-scale grids produced more complete energy spectra. At similar normalized streamwise location downstream of the grid, the classical grid did not show an easily distinguishable inertial subrange of turbulent motions as defined by Kolmogoros -5/3 law. All the multi-scale grids showed a clear inertial subrange of turbulent motions which spanned almost a decade of wavenumbers.

It can thus be concluded that multi-scale grids can be successfully implemented in an internal flow regime to passively generate high turbulence intensities with predictable and repeatable homogeneity characteristics. This is done by carefully combining elements of truly homogeneous classical grids and truly fractal grids into the so-called multi-scale grid. This work could certainly be expanded further to incorporate a parametric survey of bar thicknesses, thickness ratios, distances between the thick bars, and many such geometric variables.


