A new wind tunnel setup and evaluation of flow characteristics with/without passive devices

Yong Bai
University of Windsor

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A NEW WIND TUNNEL SETUP AND EVALUATION OF FLOW CHARACTERISTICS WITH/WITHOUT PASSIVE DEVICES

by

Yong Bai

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Civil and Environmental Engineering
in Partial Fulfillment of Requirements for the Degree of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada

2015

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AUTHOR’S DECLARATION OF ORIGINALITY

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ABSTRACT

The spire-roughness-element technology is the most widely used approach in a low speed wind tunnel simulation. In the current study, this technology will be applied in a new wind tunnel facility at the University of Windsor. After setting up all the instrumentations and developing data acquisition and analysis software, the flow quality of the empty wind tunnel is evaluated first. The noise sources which cause distortion of the raw data have been identified. Subsequently, the flow properties at the test section with the presence of spires and roughness elements have been measured. Wind speed profiles, turbulence intensity profiles, integral length scale and power spectrum are studied. A very important phenomenon was observed that the exponent $\alpha$ of the power law wind speed profile varies monotonically with respect to the frontal area density of the roughness element.
ACKNOWLEDGEMENTS

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NOMENCLATURE

\( A, B, n \) 
constants in the King’s law

\( A_0, A_1 \) 
constants in the unicurve transfer function

\( A_P \) 
block top surface area

\( A_s \) 
total frontal area of all spires

\( A_T \) 
block floor area

\( b \) 
base of the triangle

\( C_0, C_1, C_2, C_3, C_4, C_5 \) 
calibration coefficients for hot-wire probe

\( C_{D_0} \) 
drag coefficient of each spire

\( C_f \) 
effective surface friction coefficient

\( d \) 
zero-plane displacement, or the width of a wind tunnel

\( DAQ \) 
Data Acquisition

\( D_x \) 
length of the influence area of a block

\( D_y \) 
width of the influence area of a block

\( \frac{d\bar{u}}{dz} \) 
shear of the mean wind speed

\( E \) 
anemometer voltage

\( E(f) \) 
energy of an eddy

\( f_{\text{cut-off}} \) 
cut-off frequency of a low-pass filter

\( f_m \) 
fan motor frequency
\( H \) height of a wind tunnel

\( h \) height of spires

\( I, I_u \) turbulence intensity

\( k \) Von Kármán constant

\( l_m \) mixing length

\( L \) Obukhov length

\( L_x \) length of the block

\( L_y \) width of the block

\( N \) sampling number

\( N_s \) number of spires

\( P_{\text{dynamic}} \) velocity pressure

\( R_x(\tau) \) auto-correlation function

\( S_u(k) \) power spectrum density

\( SR \) sampling rate

\( T \) sampling time

\( T_I \) integral time scale

\( t_0 \) sampling starting time

\( \bar{v} \) lateral wind speed

\( v' \) lateral fluctuating component
\( u_r \) known wind speed at a reference height

\( u(z) \) wind speed at height \( z \)

\( \bar{u} \) longitudinal mean wind speed

\( u' \) longitudinal fluctuating component

\( u_* \) friction (or shear) velocity

\( u_{rms}, \sigma \) longitudinal turbulence strength

\( \bar{U} \) mean wind speed

\( U_e \) value of \( U \) above the boundary layer

\( \bar{u}'w' \) constant momentum flux

\( X_0 \) distance from station 2 to station 3

\( \bar{w} \) vertical fluctuating component

\( w' \) vertical fluctuating component

\( x(t) \) time series sampled according to the Nyquist criteria

\( z \) height above tunnel floor

\( z_0 \) surface roughness length

\( \bar{z_H} \) height of the block

Greek Symbols

\( \alpha \) exponent of power-low wind speed profile
$\Lambda_x$  longitudinal length scale

$\delta$  height of boundary layer

$\rho$  air density

$\rho_x(\tau)$  auto-correlation coefficient of the samples

$\psi$  stability term

$\varepsilon$  energy cascade rate

$\bar{\lambda}_f$  roughness frontal area density

$\bar{\lambda}_p$  roughness plan area density

$\theta$  blockage factor
CHAPTER 1 INTRODUCTION

1.1 Background

Wind tunnel is an important research tool in the field of wind engineering. It has an extensive application, which includes studying wind-induced load on and response of structures, investigating wind-related environmental issues, evaluating pedestrian level wind comfort and assessing aerodynamics feature of vehicles. Compared to full-scale measurement, the cost of wind tunnel test is much lower. In addition, under controllable lab conditions, test is repeatable which ensures the accuracy of the results. Thus, wind tunnel tests remain as the most popular measure to obtain wind-related information.

A new wind tunnel granted by Canada Foundation for Innovation (CFI) was constructed at the University of Windsor in December, 2012 (Figure 1.1). It will be referred as the CFI wind tunnel in the rest of the document. This is an open-loop low-speed atmospheric boundary layer wind tunnel, designed to perform aerodynamic studies of various civil structures and wind-related environmental issues.

Figure 1.1 CFI wind tunnel at the University of Windsor
Figure 1.2 illustrates the overall layout of the CFI wind tunnel. As can be seen from the figure, this wind tunnel has a total length of 17.6m. It consists of the inlet bell, the contraction part, the flow development region, the test section, the transition part, the fan house and the diffuser. The size of the test section is 1.8 m wide by 1.8 m high.

![Figure 1.2 Layout of CFI wind tunnel at the University of Windsor](image1)

On the floor of the test section, there is a turn table with a diameter of 1.5m, as given in Figure 1.3. It can be rotated by 360°. By mounting models on the turn table and rotating it, it allows to simulate the scenario of wind blowing from different directions on the testing model. The airflow is generated by a 7-blade axial-flow fan which has a diameter of 1.7m.

![Figure 1.3 Turntable and traverse system](image2)
The electric motor of the fan, shown in Figure 1.4, has a power of 110 kw. Honeycomb screen is mounted at the end of the inlet contraction part. It is used to reduce large turbulent eddies. As can be seen from Figure 1.5, the honeycomb has hexagonal shape and the thickness of the screen is 12 mm. The designed maximum wind velocity at the test section is 15 m/s.

Figure 1.4 7-Blade axial flow fan

Figure 1.5 Honeycomb screen

1.2 Motivation

The CFI wind tunnel is a new facility. It is necessary to set up all required instrumentations and evaluate the flow quality in the empty tunnel prior to any other tests. In addition, it is designed for conducting wind-related researches on civil structures and envi-
environmental issues. These all occur within the atmospheric boundary layer close to the ground surface, where various man-made structures and other obstacles are present. Depending on the terrain condition, the characteristics of the approaching wind could be considerably affected. When studying wind-induced effects on structures in the wind tunnel, it is of utmost importance to faithfully reproduce the terrain condition at the site. It is usually achieved by setting up passive devices in the upstream of the test section. The effect of different types of passive device and their various combinations on the flow characteristics at the test section needs to be studied and properly understood in order to successfully simulate atmospheric boundary layer flow associated with different terrain conditions.

1.3 Objectives

The objectives of the current project are as follows:

1. Set up instrumentations in the CFI wind tunnel. Design and manufacture fixtures and clamps used to support Pitot static tube and hot-wire anemometer. Develop a new data acquisition system for these sensors and software for data sampling and treatment.

2. Evaluate the flow quality in the empty wind tunnel. Determine the relation between the fan motor frequency and the generated wind speed, as well as the maximum achievable wind speed of the CFI wind tunnel. Examine the uniformity and symmetry of the flow field at the testing section and the free stream turbulence intensity level.

3. Design and manufacture two types of passive device, i.e. spire and roughness element,
to be used in the simulation of atmospheric boundary layer in the CFI wind tunnel.

4. Study the impact of different passive device arrangements on the flow characteristics in the wind tunnel. The testing cases will include: spires-only, roughness-elements-only, and the combination of spires and roughness elements.

5. Verify Irwin’s approach for spire design in terms of spire height and the generated boundary layer thickness.

6. Explore the relation between the exponent in the power law mean wind speed profile and the frontal area density of roughness elements.
CHAPTER 2 LITERATURE REVIEW

Wind tunnel is an important tool used in aerodynamic research to study the effects of air past solid objects. The earliest wind tunnels were built in the late 19th century when many attempted to invent successful heavier-than-air flying machines. Later, the scope of wind tunnel study was much expanded to other areas. For example, to study the effects of wind on man-made structures or objects, to investigate wind-related environmental issues such as air pollution, soil erosion and snow drifting. In these kinds of studies, it is required to simulate the interaction between the wind and the objects submerged in the lowest few hundred meters of the atmosphere. This layer is known as the surface layer, which is the bottom layer of the atmospheric boundary layer (ABL). The wind tunnel designed for this purpose is called atmospheric boundary layer wind tunnel (ABLWT). In this chapter, the fundamentals and theories of ABL will be reviewed, followed by the various approaches of designing an ABLWT.

2.1 Atmospheric Boundary Layer

The characteristics of ABL are directly influenced by its contact with the ground surface, the temperature, and the humidity of air. In a clear day, the ABL can be typically divided into several sub-layers. The bottom sub-layer is called the surface layer. Due to presence of various obstacles on the ground surface, wind flow close to the ground would be retarded. Thus, there is a vertical gradient in the wind speed distribution. Commonly, it extends several hundred meters above the Earth's surface. As shown in Figure 2.1.
**Logarithmic wind velocity profile**

Majority of the human activities occur in the surface layer. Despite the effect of a complex ground surface on turbulent flow, the theory of the surface layer is more developed than that for the boundary layer as a whole because the presence of ground surface limits the size of the eddies. Further, a large number of ground-based measurement campaigns have been carried out using instrumented masts. Within the surface layer, turbulent fluxes of heat and momentum are usually assumed as constants. For example, in the case of a convective boundary layer, the sensible heat flux at the top is typically 90% of the ground value. Thus, it is reasonable to assume it to be constant through the surface layer. Similar reasoning applies to momentum, and the constant momentum flux $\bar{u'}w'$ is defined as

$$u_* = \sqrt{-\bar{u'}w'}$$  \hspace{1cm} (2.1)

where $u_*$ is the friction (or shear) velocity, typically around $0.2\text{m/s}$ in the day and $\bar{u'}w'$ is always negative in the surface layer, $u'$ and $w'$ are respectively fluctuating components of the horizontal and vertical velocity.

Prandtl (1904) developed a model, in terms of mixing length, to describe momentum transfer using turbulence Reynolds stresses within a Newtonian fluid boundary layer.
by means of an eddy viscosity. The mixing length $l_m$ is the typical depth of a surface layer in the vertical direction. Actually, a surface layer is much shallower than its width, thus the mixing length can be considered as the radius of a typical eddy. This leads to the following relationship between the friction velocity, the mixing length and the shear of the mean wind in the surface layer:

$$ u_* = l_m \frac{d\bar{u}}{dz} \tag{2.2} $$

Since $u_*$ is a constant along height, if $l_m$ is known, then the wind shear and hence the vertical wind speed variation can be determined. As discussed earlier, when the flus Richardson number equals to zero, the surface layer becomes neutral and stable. The variation in the potential temperature, which is the temperature that a parcel of air would have if it brought adiabatically to some reference pressure, would not play an active role. It turns out that the mixing length would only dependent on the reference height $z$, and the eddy size would increase linearly with respect to height, i.e.

$$ l_m = kz \tag{2.3} $$

where $k$ is the Von Kármán constant.

Substitute Eq. (2.3) into Eq. (2.2) yields

$$ \frac{d\bar{u}}{dz} = \frac{u_*}{kz} \tag{2.4} $$

If assume that the wind speed is zero at height $z_0$, and integrate Eq. (2.4), it gives

$$ \int_0^{u(z)} d\bar{u} = \frac{u_*}{k} \int_{z_0}^z \frac{dz}{z} $$

$$ u(z) = \frac{u_*}{k} \ln \left( \frac{z}{z_0} \right) \tag{2.5} $$

where $k$ is the Von Kármán constant, which is roughly 0.4 for all turbulent fluids, $z_0$ is the surface roughness length, defined as the height where the wind speed according to the
logarithmic profile falls to zero. Eq. (2.5) describes the logarithmic wind velocity profile, as shown in Figure 2.2

![Logarithmic Wind Velocity Profile](image)

Figure 2.2 Logarithmic wind velocity profile (after Garratt, 1992)

When wind blows over an array of densely packed objects, such as a forest, a city, and so on, an offset in height should be introduced so that the wind velocity profile moves upward by a displacement $d$. Thus Eq. (2.5) becomes:

$$u(z) = \frac{u_s}{k} \ln \left( \frac{z - d}{z_0} \right)$$

(2.6)

where $d$ is the zero-plane displacement.

Under non-neutral conditions, a stability term $\psi$, is introduced to Eq.(2.6), i.e.

$$u(z) = \frac{u_s}{k} \ln \left( \frac{z - d}{z_0} \right) + \psi(z, z_0, L)$$

(2.7)

where $L$ is the Obukhov length and $\psi$ is a stability term.

Although the mixing length model is only a rough approximation, the logarithmic wind velocity profile has been verified by many field data measured by different researchers. In the lowest 10 to 20 m of the surface boundary layer, the logarithmic wind velocity profile is generally considered to be a reliable description of the mean wind velocity varia-
tion. To gain more insights into the characteristics within the surface layer, the key parameters governing the logarithmic wind velocity profile will be reviewed respectively.

**Surface Roughness Length** $z_0$

Surface roughness length $z_0$ is equivalent to the height at which the wind speed theoretically becomes zero in a logarithmic profile. In reality, wind speed at this height no longer follows the mathematical description of the profile. It is named such that it is typically related to the height of terrain roughness elements. Although this is not a physical length, it can be considered as a length scale representing the roughness of the surface. As an approximation, it is roughly one-tenth of the height of the surface roughness elements. Table 2.1 lists the relation between some typical terrain conditions and the corresponding roughness length.

<table>
<thead>
<tr>
<th>Terrain Description</th>
<th>Roughness Length $z_0$ (m)</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open sea, fetch at least 5 km</td>
<td>0.0002</td>
<td>Lewis, 1976</td>
</tr>
<tr>
<td>Mud flats, snow; no vegetation, no obstacles</td>
<td>0.005</td>
<td>Callaghan, 1976</td>
</tr>
<tr>
<td>Open flat terrain; grass, few isolated obstacles</td>
<td>0.03</td>
<td>ESDU, 1972</td>
</tr>
<tr>
<td>Low crops; occasional large obstacles</td>
<td>0.1</td>
<td>Deacon, 1953</td>
</tr>
<tr>
<td>High crops; scattered obstacle</td>
<td>0.25</td>
<td>Leurs, 1981</td>
</tr>
<tr>
<td>parkland, bushes; numerous obstacles</td>
<td>0.5</td>
<td>Garratt, 1978</td>
</tr>
<tr>
<td>Regular large obstacle coverage</td>
<td>1.0</td>
<td>Allen, 1976</td>
</tr>
<tr>
<td>City centre with high- and low-rise buildings</td>
<td>$\geq 2$</td>
<td>Ming, 1983</td>
</tr>
</tbody>
</table>
Despite the progress in the past few decades to use surface roughness length to account for the effects of ground surface covered with small roughness elements on the wind velocity profile, due to high cost of field measurements, much effort has been made to find a better model to reproduce the wind velocity profile in ABLWT. This is typically achieved by the combined use of turbulence generation devices, such as spires, and roughness elements.

Refer to Figure 2.3, the roughness plan area density $\bar{\lambda}_p$ is defined as the ratio between the block top surface area $\bar{A}_p$ and the block floor area $\bar{A}_T$, i.e.

$$\bar{\lambda}_p = \frac{\bar{A}_p}{\bar{A}_T} = \frac{L_x L_y}{D_x D_y}$$  \hspace{1cm} (2.8)

where $L_x$ is the length of the block (along the wind direction);

$L_y$ is the width of the block (transverse to the wind direction);

$D_x$ is the length of the influence area of a block (along the wind direction);

$D_y$ is the width of the influence area of a block (transverse to the wind direction);

and the roughness element frontal area density $\bar{\lambda}_f$ is defined as:

$$\bar{\lambda}_f = \frac{\bar{A}_F}{\bar{A}_T} = \frac{\bar{z}_H L_y}{D_x D_y}$$  \hspace{1cm} (2.9)

where $\bar{z}_H$ is the height of the block;

Lettau (1969) depicted the relation between the surface roughness length and the alignment of roughness elements along the wind tunnel floor based on wind tunnel testing results, which was

$$z_0 = \frac{1}{2} \bar{z}_H \times \bar{\lambda}_f$$  \hspace{1cm} (2.10)
In the experimental study by Counihan (1971), roughness cubes were placed in different alignments downwind of elliptic wedge eddy generators. By analyzing the velocity profiles, an empirical formula different from Lettau's was proposed:

\[ z_0 = \bar{z}_H [1.08 \bar{\lambda}_P - 0.08] \]  

(2.11)

The empirical formula proposed by Lettau (1969) is applicable to \( \bar{\lambda}_p < 0.06 \), whereas that by Counihan (1971) is valid for \( 0.1 < \bar{\lambda}_p < 0.25 \).

In the empirical formula proposed by Jackson (1981), the surface roughness length is determined by the roughness frontal area density \( \bar{\lambda}_f \), the drag coefficient \( C_D \), the roughness element height \( d \), and the mixing length \( l \) or \( l_h \):

\[ \frac{\bar{z}_H - d}{z_0} = \exp \left( \frac{\kappa h}{\alpha l_h} \right) \]  

(2.12)

where \( \alpha = C_D \bar{\lambda}_f \bar{z}_H^2 / 4l^2 \)

Theurer (1993) introduced the roughness plan area density \( \bar{\lambda}_p \) in his roughness length prediction model and found that Lettau’s formulation of \( z_0 \) would fail for plan area density higher than 0.25. Wieringa (1993) pointed out the deficiencies in these empirical formulae and suggested seven possible ways to refine them. When analyzing five sets of
wind tunnel testing data, Peterson (1997) noticed that uncertainty in the prediction of wind velocity profile could occur due to selection of different fitting range of data along height. This implies that the effect of zero-plane displacement on the surface roughness length cannot be neglected. A comparison between these empirical models showed that all of them are valid under the conditions of high roughness frontal or plane area density (Duijim, 1999). Bottema (1997) developed a new model to deal with cases of low roughness frontal or plane area density, or non-uniform dimensions of roughness elements. Results showed that the consistency between Bottema's and Lettau's model was up to 95%.

The empirical formulae reviewed above are all developed based on wind tunnel testing results. Before 1998, it was believed that the velocity profile was strongly dependent on properties of roughness elements, such as dimension, shape, and alignment on a wind tunnel floor. Since these formulae still cannot satisfactorily predict the velocity profile, further improvements were proposed by different researchers by introducing another parameter, which is the zero-plane displacement $d$. In the refined formulae proposed by Macdonald et al (1998), besides dimension and alignment of roughness elements as well as the zero-plane displacement, two new parameters, i.e. the drag coefficient and the von Kármán constant were included based on the principle of conservation of momentum. Jia et al (1998) found that when the roughness frontal area density was reduced by over 20%, the surface roughness length would decrease. This agrees with the finding by Rapauch and Thom (1980).

It can be seen from the above literature that surface roughness length, which describes the terrain condition, is a very important aerodynamic parameter in describing wind
velocity profile. When simulating such an effect in the wind tunnel using cubic roughness elements, the dimension, shape and alignment of roughness elements would strongly affect the generated wind velocity profile. In the current study, cubic roughness elements will be used as part of the passive device to produce natural atmospheric boundary layer above certain type of terrain condition in the CFI wind tunnel.

**Zero-plane displacement $d$**

Thom and Raupach (1981) defined the zero-plane displacement, $d$, as the height in meters above ground where wind speed becomes zero as a result of the presence of obstacles such as trees and buildings. In practice, it is evaluated from the logarithmic wind profile by plotting the logarithm of height versus wind speed under near neutral conditions. Table 2 gives the zero-plane displacement associated with a number of typical ground surface types.

**Table 2.2 Aerodynamic properties of surfaces (Monteith and Unsworth, 1990)**

<table>
<thead>
<tr>
<th>Surface</th>
<th>Roughness Length(m)</th>
<th>Zero Plane Displacement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>$0.1 - 10^{-4}$</td>
<td>N/A</td>
</tr>
<tr>
<td>ice</td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>snow</td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>sand</td>
<td>0.0003</td>
<td>N/A</td>
</tr>
<tr>
<td>soil</td>
<td>0.001 - 0.01</td>
<td>N/A</td>
</tr>
<tr>
<td>grass, short</td>
<td>0.001 - 0.003</td>
<td>&lt; 0.07</td>
</tr>
<tr>
<td>grass, tall</td>
<td>0.04 - 0.1</td>
<td>&lt; 0.06</td>
</tr>
<tr>
<td>crops</td>
<td>0.04 - 0.2</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>orchards</td>
<td>0.5 - 1</td>
<td>&lt; 4</td>
</tr>
<tr>
<td>deciduous forest</td>
<td>1 - 6</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>conifer forest</td>
<td>1 - 6</td>
<td>&lt; 30</td>
</tr>
</tbody>
</table>
On the other hand, the zero-plane displacement can be considered as the height at which the mean drag appears to act (Jackson, 1981). Stull (1988) estimated that the zero-plane displacement should vary between 0.6 to 0.8 times the height of the forest canopies. The results by Arya (1998) verified Stull's prediction. However, the roughness length and zero-plane displacement yielded from measurement results over agricultural crops and forests are not consistent, since the latter has distinct and different leaf area profiles. From a theoretical perspective, Shaw and Pereira (1982) used a higher order turbulence closure model to examine the inter-relation between the zero-plane displacement, the surface roughness length, the leaf area index, the canopy drag and the distribution of leaf area.

Theurer (1993) normalized the zero-plane displacement by the roughness element height. It was found that the dimensionless zero-plane displacement was 1.67 times of the roughness frontal area density $\lambda_f$. This convinced many researchers that the conventional empirical models of surface roughness length should be corrected by the zero-plane displacement. To further confirm this, Spanton et al (1996) conducted a series of field measurements to obtain roughness frontal area density at different districts in some cities in UK. Results showed that $\lambda_f$ is 50-60% in business zones and 20-40% in industrial zones. This suggests that the Lettau's model, of which the effect of zero-surface displacement is neglected, would overestimate the surface roughness length. After comparing data yielded from seven different calculation methods, Peterson (1997) indicated that the zero-plane displacement should be included in the surface roughness length calculation model.

Shear Velocity $\mu_e$
Shear velocity $\mu_*$ is a scaling velocity that is related to momentum transfer. It is an important parameter in geophysical flows. It is typically derived from logarithmic flow velocity profile by applying ordinary least square regression. This parameter would also strongly affect the calculation results of surface roughness length (Bottema et al, 1998). Raupach and Thom (1980) indicated that due to the uncertainty of turbulent kinetic energy, the calculated $\mu_*$ is different from the measurement. Thus, the approach of using turbulent kinetic energy to determine $\mu_*$ is hardly used now. Cook (2003) noticed a 15% discrepancy in the shear velocities measured by Iyengar and Farell (2001). According to his speculation, this could be caused by the drag acting on a block could not be totally converted into inner Reynolds stress. The correct approach is to measure Reynolds stress directly. A number of new methods for calculating shear velocity have been proposed recently. Liu et al (2003) measured the turbulence intensity close to a wind tunnel wall and then substituted the surface roughness length into the velocity profile formula to obtain shear velocity. In the model proposed by Hollingsworth (2003), various free stream parameters, such as the mean flow velocity, the integral length scale and the turbulence intensity were all considered in the formulation.

**Power-law wind velocity profile**

The power-law wind velocity profile is often used as a substitute for the logarithmic wind velocity profile in non-complex terrain up to a height of about 200 m above ground level. It can be expressed as:

$$\frac{u(z)}{u_r} = \left(\frac{z}{z_r}\right)^\alpha$$  (2.13)
where \( u(z) \) is the wind speed (in \( m/s \)) at height \( z \) (in meter);

\( u_r \) is the known wind speed at a reference height \( z_r \);

\( \alpha \) is an exponent, which typically varies from about 0.1 on a sunny afternoon to about 0.6 during a cloudless night. Under neutral stability conditions, it is approximately \( 1/7 \), or 0.143.

In wind resource assessments, a constant \( \alpha \) value of \( 1/7 \) is commonly assumed. However, when a constant power law exponent is used, the surface roughness length, the zero-plane displacement (Touma, 1977), or the stability of the atmosphere (Counihan, 1979) are excluded in the prediction of velocity profile. In places where trees or structures impede the near-surface wind, this may yield quite erroneous estimates. Even under neutral stability conditions, an exponent of 0.11 is more appropriate to be used for the over open water (e.g. for offshore wind farms) than 0.143, which is more suitable for terrain over open land surfaces (Meindl and Gilhousen, 1994). The larger the power-law exponent is, the more considerable the gradient in the vertical profile of streamwise wind speed will be. The four types of terrain roughness categories implied by Exposures A, B, C and D in ASCE 7-95 are given in Table 2.3.

Although power-law is a useful engineering approximation to estimate the average wind speed profile, the actual profile deviates from this idealized relationship. As discussed by Irwin (1979), the exponent in the power-law wind velocity profile is a function of stability, surface roughness length and the height range within which it is determined. In the lowest 10–20 m of the planetary boundary layer, the logarithmic profile can generally offer more reliable estimation on the velocity profile than the power-law profile. However, the
power-law profile has a wider applicable range. Bergstom (2001) conducted open duct turbulent experiments on smooth and coarse walls. The friction velocity was determined by the power-law profile since it was noticed that the logarithmic profile layer was very thin and could be neglected. Afzal (2001) studied a turbulent boundary layer without neglecting pressure gradient. It was found that the transient layer could be described by either the power-law or the log-law. In particular, as Reynolds number increases, the power-law profile and logarithmic profile coincides with each other.

Table 2.3 Terrain roughness category and exposure type (ASCE 7-95)

<table>
<thead>
<tr>
<th>Exposure type</th>
<th>Terrain Description</th>
<th>$\alpha$</th>
<th>$z_0$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Open sea, Fetch at least 5 km</td>
<td>0.12</td>
<td>0.002</td>
</tr>
<tr>
<td>C</td>
<td>Mud flats, snow; no vegetation, no obstacles</td>
<td>0.16</td>
<td>0.02</td>
</tr>
<tr>
<td>B</td>
<td>Parkland, bushes; numerous obstacles</td>
<td>0.22</td>
<td>0.5</td>
</tr>
<tr>
<td>A</td>
<td>Regular large obstacle coverage</td>
<td>0.33</td>
<td>1</td>
</tr>
</tbody>
</table>

**Turbulence Intensity**

Turbulence in natural wind causes fluctuation of wind velocity in time and space. Figure 2.4 shows a segment of typical wind velocity time history.

The movement of wind is comprised of three velocity components, which are along respectively the three Cartesian coordinate axis directions $x$, $y$ and $z$. $u$ is the horizontal stream wise velocity, $v$ is the horizontal lateral velocity and $w$ is the vertical velocity. These three velocity components can be further expressed as the superposition of a mean component and a zero-mean fluctuation component (Reynolds’ averaging), i.e.
\[
\begin{align*}
\mathbf{u} &= \bar{\mathbf{u}} + \mathbf{u}' \\
\mathbf{v} &= \bar{\mathbf{v}} + \mathbf{v}' \\
\mathbf{w} &= \bar{\mathbf{w}} + \mathbf{w}'
\end{align*}
\]

(2.14)

where, \( \bar{u}, \bar{v}, \bar{w} \) are mean components of velocity, and \( u', v', w' \) are the fluctuating components of velocity. In the case of vertical velocity, its mean component is typically zero over flat terrain.

![Figure 2.4 Mean and fluctuating components of a wind velocity time history](image)

The mean wind speed is defined as:

\[
\bar{U} = \frac{1}{T} \int_{t_0}^{t_0+T} U dt = \frac{1}{N} \sum_{i=1}^{N} \bar{U}_i \text{(discrete)}
\]

(2.15)

\[
= \frac{1}{T} \left( \bar{u}^2 + \bar{v}^2 + \bar{w}^2 + \bar{u}'u' + \bar{v}'v' + \bar{w}'w' \right)^{1/2}
\]

where \( T \) is sampling time, \( t_0 \) is sampling starting time, \( N \) is sampling number, and the longitudinal turbulence strength is

\[
\bar{u}_{rms} = \sigma = \sqrt{\bar{u}^2} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (u')^2}
\]

(2.16)

Turbulence is often considered as the superposition of eddies with different sizes transported by the mean flow. One of the main characteristics of turbulence is the turbulence intensity, which plays a key role in the ABL theory. It is defined as the ratio between
the root-mean-square of the fluctuating component of the longitudinal wind velocity and its time-averaged mean value, i.e.

\[ I = \sigma / \overline{U} \]  \hspace{1cm} (2.17)

Similar definitions can be applied to the lateral and vertical velocities.

An empirical formula for estimating turbulence intensity of ABL flow is provided by ESDU 75001 (1975), i.e.

\[ I_u = \frac{1}{\ln(z/z_0)} \left[ 0.867 + 0.566 \log z - 0.246 \left( \log z \right)^2 \right] \lambda \]  \hspace{1cm} (2.18)

\[ \lambda = \begin{cases} 0.76/z_0^{0.07} & z_0 > 0.02m \\ 1.0 & z_0 \leq 0.02m \end{cases} \]  \hspace{1cm} (2.19)

where \( z_0 \) is the surface roughness length, and \( z \) is the height.

Zhou et al (2002) proposed a general formula for estimating the turbulence intensity of ABL flow, which is

\[ I(z) = c(z/10)^{-d} \]  \hspace{1cm} (2.20)

where \( c \) and \( d \) are constants related to the terrain type and are listed in Table 2.4.

<table>
<thead>
<tr>
<th>CODE</th>
<th>ASCE 7-95</th>
<th>AS1170.2</th>
<th>NBC</th>
<th>RLB-AIJ</th>
<th>EUROCODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain Class</td>
<td>c</td>
<td>d</td>
<td>c</td>
<td>d</td>
<td>c</td>
</tr>
<tr>
<td>A</td>
<td>0.450</td>
<td>0.167</td>
<td>0.453</td>
<td>0.300</td>
<td>0.621</td>
</tr>
<tr>
<td>B</td>
<td>0.300</td>
<td>0.167</td>
<td>0.323</td>
<td>0.300</td>
<td>0.355</td>
</tr>
<tr>
<td>C</td>
<td>0.200</td>
<td>0.167</td>
<td>0.259</td>
<td>0.300</td>
<td>0.200</td>
</tr>
<tr>
<td>D</td>
<td>0.150</td>
<td>0.167</td>
<td>0.194</td>
<td>0.300</td>
<td>0.204</td>
</tr>
<tr>
<td>E</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Power Spectrum of Longitudinal Fluctuating Velocity**

In the view of Kolmogorov (1941), turbulent motion of flow spans a wide range of scales from a macro scale at which the energy is supplied, to a micro scale at which energy is dissipated by viscosity. The interaction between eddies of different scales passes energy from the larger ones gradually to the smaller ones. This process is known as the turbulent energy cascade. The atmospheric power spectrum typically consists of three sub-ranges: the energy containing range, the inertial sub-range, and the dissipation range. Turbulence in the energy containing range is produced by shear and buoyancy. In the inertial sub-range, energy is neither produced nor destroyed, but cascades from larger to smaller eddies. Let us denote \( \varepsilon \) as the energy cascade rate. By dimensional analysis, the spectrum in the inertial sub-range can be obtained as

\[
S_u(k) = \alpha \varepsilon^{2/3} k^{-5/3}
\]

where \( \alpha \) is the Kolmogorov constant, \( k \) is a wavenumber, defined by \( 2\pi/\text{wavelength} \). The value of \( \alpha \) has been determined experimentally to be about 1.5 (Pope, 2000). The \(-5/3\) power law of the energy spectrum has been observed to hold well in the inertial range, that is, for those intermediate size eddies. However, an alternative theory that predicts a \(-2\) power law has also been proposed (Saffman, 1968; Long, 1997; 2003).

### 2.2 Simulation of atmospheric boundary layer in wind tunnel

Simulation of atmospheric boundary layer in wind tunnel can be achieved by natural formation or introducing man-made devices. The former approach requires very long test section. Typically, a boundary layer with a thickness of 0.5-1.0 m can be naturally
formed when flow passes a 20-30m long rough floor development section. The boundary layer wind tunnel at Western university uses this method to simulate ABL. However, this approach is rarely utilized now due to the requirement of long test section. But rather, the latter approach, i.e. to form ABL in the wind tunnel using different types of man-made devices, is the primary technique adopted by many researchers in different wind tunnel labs. Depending on whether or not controllable devices are part of the simulation tool, the latter approach can be further classified as passive simulation method and active simulation method. The essential difference between these two is whether or not the device is capable of supplying energy into the flow field in the wind tunnel. Various man-made devices used in the passive and active simulation methods to generate ABL in wind tunnel will be reviewed in the next two subsections.

2.2.1 Active simulation approaches

Due to limitation of wind tunnel size, it is difficult to generate large scale turbulence using passive simulation methods. By supplying additional energy with appropriate frequency components to the wind tunnel flow field, the active simulation approaches can help to increase the low frequency components in turbulent flow, and thus improve the simulation results on integral length scale and power spectra of longitudinal fluctuating velocity. However, the high cost of active simulation devices limited its utilization in practice.

Nishi et al (1999) reproduced the vertical Reynolds stress coefficient in a two dimensional wind tunnel, which had eleven fans arranged vertically. Each fan was connected to a computer through a motor drive. The dimension of the two test sections, in terms of
length×width×height were respectively 3.8m×0.18m×1.0m and 5.0m×1.0m×1.0 m. The maximum wind velocity of the tunnel was 11 m/s. Oscillating airfoils were installed at the mid-section of the tunnel to add vertical turbulence to the main flow. All fans and oscillating airfoils were controlled independently by computers.

Various types of turbulent flow characteristics could be simulated by modifying the computer program. Using this kind of active simulation devices, Nishi and his colleagues also reproduced coherent motions similar to the natural turbulent flow.

The 1MW boundary layer wind tunnel at the Monash University used active simulation techniques to reproduce ABL over suburban terrain in the wind tunnel. A large trip board with adjustable oscillation stroke and frequency was hinged on the tunnel floor and activated by a pneumatic cylinder to flap in the wind. Cheung et al (2001) used this active device to simulate more real atmospheric turbulence effects on large structures and pollutant dispersion studies.

Pang and Lin (2008) developed a technique of using oscillating spires to actively simulate the turbulent boundary layer (Figure 2.5). A conventional spire is symmetrically split into two parts, which can flap with a certain frequency. This device was proven to increases the turbulence energy and the integral scale.

![Figure 2.5 Vibrating spires (Pang and Lin, 2008)](image-url)
2.2.2 Passive simulation approaches

In the passive simulation approach, man-made devices, such as fences, uniform grids, spires and roughness elements, or combination of some of them, are typically used to artificially thicken the boundary layer. To reproduce flow characteristics over certain type of terrain condition at the test section, it is required not only to reproduce the corresponding wind velocity profile, but the associated turbulence intensity, integral length scale and power spectra of the longitudinal fluctuating velocity.

Owen (1957) obtained a nearly uniform shear flow in the working section of a wind tunnel by inserting a grid of parallel rods with varying spacing, as shown in Figure 2.6. By adjusting arrangements of the rods along the vertical direction, a linear or logarithmic variation of velocity profile was produced at large distance downstream. However, the experimental results of turbulence intensity disagreed with the theoretical prediction because dissipation of turbulence energy was high.

![Figure 2.6 Arrangement of the grid and coordinate system (after Owen, 1957)](image)

Philips et al (1999) used an array of non-uniformly spaced flat plates to produce a specified velocity profile, which is shown in Figure 2.7. The fully developed duct flow could be controlled by the length of flat plate and the space between two adjacent plates.
This method was developed to simulate weak shear flow with zero vertical pressure gradients.

![Schematic diagram of the array of differentially spaced flat plates in wind tunnel](image)

Figure 2.7 Schematic diagram of the array of differentially spaced flat plates in wind tunnel (after Phillips, 1999)

Ham et al (1998) modified the shape of conventional spires so as to generate a low-turbulence nominal flow. The geometric shape of spire was discontinuous. Several rows of chain were used as roughness elements and placed behind an upstream barrier. A very good agreement between the laboratory and field wind velocity characteristics was observed.

Counihan (1969) developed a method to simulate an ABL in a wind tunnel. The eddy generators consisted of triangular, cranked triangular, plane elliptic and elliptic wedge shapes. The shape of the elliptic wedge generator is shown in Figure 2.8. Counihan carried out an experiment in the CERL boundary layer wind tunnel which has a working section 24" wide, 7-30" high and 5’ long.

The tests were conducted at a free stream velocity of 9m/s and without the presence of a barrier or surface roughness. Counihan found that a working section length between four and five boundary layer thicknesses was required to produce the simulated flow. The
general characteristics of boundary layer flow were formed at a distance of three boundary layer thicknesses from the generator trailing edges. To simulate flow condition over rural terrain, Counihan's method can produce satisfactory simulation results in wind tunnel.

Figure 2.8  Shape of elliptic wedge generator

Standen (1972) proposed a method to generate thick shear layer using an array of standard half-width spires. These spires, with spacing of half spire height, were placed at the entrance to the tunnel working section, as shown in Figure 2.9. Standen made various investigations by changing the height of spires from 6" to a maximum of 7", and increasing wind speed from 15m/s to 30m/s. He also developed several other types of spires, as shown in Figure 2.10.
Spires shown in Figure 2.10(a) and Figure 2.10(b) are triangular plates without central section and Figure 2.10(c) with a rear splitter.

Standen's method can provide a good approximation to the ABL up to 450 m above the ground surface. However, he thought the method need to be refined. Especially, the ratio of boundary layer thickness to spire height is not a constant for all spire sizes.

Irwin (1979) found that Standen's method might produce very high spire drag and a boundary layer with too high $\alpha$ value. At the same time, he thought any roughly triangular shaped spires would give an acceptable boundary layer simulation at six spire heights downstream provided they had the correct overall drag coefficient. In other words, the fine
details of the spire shape are not that important. Based on the overall momentum balance at different stations in the wind tunnel, he introduced a new method to design spires. The shape of the spire was triangular. A set of spires were placed at the entrance to the test section and followed by an array of cubes. The mean velocity profile, longitudinal turbulence intensity and integral length scale compare well with neutral planetary boundary layer data, and other turbulence properties, such as turbulence spectrum, are similar to those at full scale measurements.

Since the spire-roughness element technique was proposed, it was widely used by many wind tunnel labs to simulate a wide range of surface layer. Although the simulation data reported by individual projects tend to be scattered and there is no overall assessment available, they lied almost entirely within the range of the full scale data. So, the eddy generators used in the CFI wind tunnel will be designed using Irwin’s method.
CHAPTER 3 CFI WIND TUNNEL SETUP

3.1 Instrumentations

The wind speed measurement system in the CFI wind tunnel is shown in Figure 3.1. It includes a Pitot static tube, a Miniature CTA 54T30 Hot-wire anemometer, an NI9222 data acquisition card and a computer. Analogue signals from the Pitot tube and the hot-wire anemometer are collected firstly into NI9222 and then transferred into the computer. These signals will be analyzed and treated by software developed in the Labview® environment.

The instrumentations used in the current study are described as follows:

3.1.1 Pitot Static Tube

A Pitot static tube is used to monitor the free stream mean wind speed in the wind tunnel during tests, which is used as the reference wind speed for analyzing experimental data. It measures the dynamic pressure of the air by differencing the total pressure and the static pressure. The static pressure is exerted on the sidewall of the tube whereas the total pressure (also known as the stagnation pressure) is taken at the point tip of the tube. The dynamic pressure is called the velocity pressure. It can be used to calculate the wind speed.
Usually, a Pitot static tube has two tubes, one inside the other, to sense both pressures simultaneously. By connecting these two tubes differentially to a manometer, the velocity pressure can be directly obtained and the corresponding air velocity can be determined by applying the formula

\[ P_{\text{dynamic}} = \frac{1}{2} \rho U^2 \]  

where \( \rho \) is the air density and \( U \) is the air velocity. The maximum accuracy of a Pitot static tube is ±2% in the laboratory application.

The Pitot static tube used in the CFI wind tunnel is Dwyer® 160E-01. It is made of 304 stainless steel. The outside diameter of the tube is 5/16” and the length of the depth indicator arm is 11-7/8”. As shown in Figure 3.2, to ensure the reference wind velocity of the wind tunnel will not be affected by the presence of the ceiling, the Pitot static tube is mounted 250mm below the tunnel ceiling in the mid-plane of the tunnel and upstream of the turn table. It is connected to a Dwyer® manometer (Series MS Magnesense® Differential Pressure Transmitter, Accuracy: ±1%) by two flexible tubes. The total pressure tap is connected to the high pressure side of the manometer and the static pressure tap to the low pressure side. The output of the manometer displayed on its LCD screen is the dynamic pressure.

Figure 3.2 Pitot static tube
The dynamic pressure reading on the LCD display is affected by the full scale range of the manometer. According to the user manual (Series 160 Stainless Steel Pitot Tube Specifics-Installation and Operation Instruction, Dwyer®, https://www.dwyer-inst.com/PDF_files/160_IOM.pdf), there are three full scale pressure ranges: 0-125 Pascal’s, 0-250 Pascal’s and 0-500 Pascal’s. A linear relation exists between the voltage signal and the pressure. For example, corresponding to the 0-10 Volts of output voltage range, for the default full scale range of 0-250 Pascal, 0 volt corresponds to 0 Pascal whereas 10 volts corresponds to 250 Pascal, and the voltage signal can be easily converted to pressure by \( P = 25V \), where \( P \) is the dynamic pressure, and \( V \) is the voltage signal. This default full scale range of pressure satisfies the requirement of the current study. In addition, the analog voltage is read by the DAQ, and sent to the computer to analyze.

3.1.2 Hot-wire Anemometer (HWA)

A hot-wire anemometer, often called Constant Temperature Anemometry (CTA), works on the basis of convective heat transfer from a heated sensing element to the surrounding fluid, the heat transfer being primarily related to the fluid velocity. CTA has good signal sensitivity and can measure instantaneous small changes in flow velocity. The characteristic of high frequency response of CTA, up to 1 MHz, makes it accurately follow transients without any time lag. Usually, CTA uses very fine wire sensors with four different types: miniature wires, gold-plated wires, fiber-film or film-sensors. Wires are normally 5\( \mu \)m in diameter and 1~2mm long, so that they create minimum flow disturbance and pro-
vide a good spatial resolution. CTA has been used for many years in flow measurement, in particular, for turbulence.

 Principally, the rate of heat loss from a sensor of CTA to the fluid is equal to the electric power delivered to the sensor. If the fluid properties and wire resistance remain constant, their relation may be expressed by the King’s law (King, 1914)

\[ E^2 = A + BU^n \]  

(3.2)

where \(E\) is the anemometer voltage and \(U\) is the fluid velocity. \(A\), \(B\), and \(n\) are constants. In practice, the value of the exponent \(n\) changes with sensor and velocity as do the values of \(A\) and \(B\) and it is therefore necessary to calibrate each sensor individually and to check this calibration frequently. There are two methods to calibrate a probe: the power law curve fitting and the polynomial curve fitting. According to the King’s law, the output voltages from a probe at two known fluid velocities should be determined first, i.e. two sets of \(E^2\) and \(U^n\) (\(n = 0.45\) is a good starting value in practice) are available. Then, a linear trend line can be created and it will give the constants \(A\) and \(B\). Vary \(n\) and repeat the trend line until the curve fitting error is acceptable. The relationship of the anemometer voltage and the fluid velocity can finally be determined. However, as \(n\) is slightly velocity dependent, the power law curve fitting is less accurate than the polynomial curve fitting.

 Two calibration approaches are designed for the polynomial curve fitting: the two-point calibration and the multi-point calibration. In the two-point calibration, two known set points are used to create a unicurve transfer function for a specific probe type. Probes with identical sensors have similarly shaped calibration curves. Dantec\textsuperscript{®} Company built a set of standard \(U-E\) data for different sensors (Product Information of Hot-Wire
Calibrator, Dantec®). The unicurve transfer function, which gives a logarithmic square relation between $E$ and $U$, is defined as

$$E = A_1[\ln^2(1 + 10U)] + A_0$$  \hspace{1cm} (3.3)

where $E$ is the anemometer voltage and $U$ is the fluid velocity. $A_0$ and $A_1$ are constants.

This function provides a robust curve fitting over a wide velocity range for the Stream-Line® Calibrator, from 0.5m/s to 60m/s, with small curve fitting errors. After constants $A_0$ and $A_1$ are determined, fifteen pairs of $U$-$E$ points are chosen from the standard $U$-$E$ data. The final individual transfer function is a 5th order polynomial shown as

$$U = C_0 + C_1E + C_2E^2 + C_3E^3 + C_4E^4 + C_5E^5$$  \hspace{1cm} (3.4)

where $C_0, C_1, C_2, C_3, C_4, C_5$ are the calibration coefficients. Applying generalized linear regression, all calibration coefficients are determined. In this way, it is possible to linearize with errors less than 1% of reading. Two-point calibration is mostly used in the 54H10 hot-wire calibrator provided by Dantec® Dynamics company.

Although the multi-point calibration approach uses a transfer function as same as Eq. (3.4) in the two-point calibration approach, it can be either carried out with a calibrator, which normally is a free jet, or in a wind-tunnel. Multi-point calibration is a traditional approach and can plot a fitting curve by using many pairs of $U$-$E$ points. It makes very good fits with linearization errors less than 1%. Usually, an Excel table is built first, as shown in Table 3.1.

The output voltages at many known velocities are tested, based on which six calibration coefficients are determined by the generalized linear regression, as shown in Figure 3.3.
Table 3.1 Multi-point Calibration

<table>
<thead>
<tr>
<th>U(m/s)</th>
<th>E(volt)</th>
<th>C5</th>
<th>C4</th>
<th>C3</th>
<th>C2</th>
<th>C1</th>
<th>C0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>1.56</td>
<td>-9975.0</td>
<td>34269.8</td>
<td>-58707.6</td>
<td>50131.7</td>
<td>-17068.7</td>
<td>#N/A</td>
</tr>
<tr>
<td>2.5</td>
<td>1.68</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td>1.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.98</td>
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<td></td>
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<td>12.5</td>
<td>2.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>2.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fitting U(m/s) | 1.3 | 2.5 | 5.0 | 7.5 | 10.0 | 12.5 | 15.0 |

Figure 3.3 Multi-point fitting curve

The CTA measurement chain in the CFI wind tunnel lab is shown in Figure 3.4.

Figure 3.4 CTA measurement chain (1. Hot-wire probe (55P16); 2. 4m cable; 3. Mini CTA 54T30; 4. Power cable; 5. Data cable)
To carry out a calibration, a jet nozzle has been designed to supply free jet and a Pitot static tube is used to measure the mean flow speed $U$ of the jet. The calibration system for the mini CTA is shown in Figure 3.5. By adjusting the switch or the pressure regulator, the flow rate at the jet outlet varies. The velocity range changes from 1m/s up to 20m/s, which covers the maximum velocity of 15m/s in CFI wind tunnel.

![Figure 3.5 Calibration system of hot-wire probe](image)

Figure 3.5 Calibration system of hot-wire probe (1. Pitot static tube; 2. Hot-wire probe (55P16); 3. Jet nozzle; 4. Pressure regulator; 5. Pressure gauge; 6. Switch; 7. AfterFilter)

When measuring flow properties in the wind tunnel, a 55P16 hot-wire probe is installed on a traverse system as shown in Figure 3.6. The movement of the traverse in the horizontal and vertical directions would allow it to measure instantaneous wind velocity at a designated point. According to the velocity information, the turbulent intensity and other wind properties could be deduced.
A probe clamp is designed and made of PTC material, as shown in Figure 3.7.

It can hold the probe and keep it in the same orientation during the movement of the traverse nuts. There are three clamps. One is placed at the end of the “Z”-shaped rod to fix the BNC connector, as shown in Figure 3.8(a); the second one is at the middle position of the “Z”-shaped rod, as shown in Figure 3.8(b), to bundle wires so as to minimize their vibration in wind; the last one is placed at the far end of the “Z”-shaped rod and clamps the probe tightly with two screws, as shown in Figure 3.8(c). One screw is used to adjust the angle between the clamp and the “Z”-shaped rod and the other one to fix the wire in the horizontal or vertical position.
Figure 3.8 Close-up of the three clamps

As shown in Figure 3.9, a “Z”-shaped rod is designed and made of steel.

![Figure 3.9 “Z”-shaped rod](image)

Its main function is to set the minimum distance close to the tunnel wall or floor in a boundary layer measurement. Due to the limitations of the traverse stroke, the boundary layer measurement could not be taken without the “Z”-shaped rod. As shown in Figure 3.10, the “Z”-shaped rod allows to measure flow properties up to 5mm from the tunnel wall or floor.
3.1.3 Traverse System

A traverse system is needed because most of wind properties are related to the spatial position. In a wind tunnel, it is used to move the probe automatically or manually during an experimental procedure. There are two issues of concern: rigidity of a traverse system and the impact of its presence on the flow pattern. Since vibration of traverse system will affect the velocity measurement, it should be designed to be rigid so that it will not vibrate or bend when it is exposed to the wind load. At the same time, the traverse system should not disturb the flow at the probe position. This may be achieved by using some fixtures, such as a “Z”-shaped rod and clamps, to mount the probe on the traverse.

A two-axis BISLIDE® traverse system (MN10-0500-M02-31) is placed in the CFI wind tunnel as shown in Figure 3.11. The traverse system has two axes. The travel distance...
is 50". The repeatability is 0.0002" and the straight line accuracy is 0.003".

Figure 3.11 Two-axis BiSlide® traverse system

To eliminate its effects on the flow, a “T” -shaped aluminum plate is fastened to the carriage and serves as a support for the “Z” -shaped rod, as shown in Figure 3.12. The traverse system is mounted on two steel plates with the standard Velmex cleats, as shown in Figure 3.13. The Z axis end plate is attached to the Y axis carriage with cleats shown in Figure 3.14. This configuration improves the rigidity of the traverse system.

Figure 3.12 “T”-shaped plate support
3.1.4 Data Acquisition System

A complete data acquisition system (DAQ) consists of hardware, sensors and actuators, signal conditioning hardware, and a computer which installs DAQ software. Sampling signals from sensors or sending signals to actuators must be manipulated by a computer. ADC or DAC plays a role to convert analog waveform to digital number values for processing, or invert to drive actuators. To sample signals, two parameters needs to be defined for the DAQ: the sampling rate and the sampling number. Usually, the sampling time
is determined as a calculated value of the sampling number over the sampling rate. All the DAQ parameters can be set by software installed on a computer.

In the CFI wind tunnel, several types of sensors and actuators are comprised in the DAQ. For the mixed-measurement testing system, an 8-slot NI CompactDAQ USB chassis (NI cDAQ-9178) shown in Figure 3.15 is used for analog inputs, analog outputs, and digital I/O.

Figure 3.15 NI cDAQ-9178

In the wind property measurement, an analog input module (NI 9222) is inserted in NI cDAQ-9178, as shown in Figure 3.16. The wires from the Pitot static tube are connected to Channel AI 0+ and 0-, and HWA to Channel AI 1+ and 1-. The measurement range is ±10 V with 16-bit resolution.

Figure 3.16 NI 9222
3.2 Data Analysis

As the properties associated with turbulent flow will be of random nature, a statistical description of the signal is necessary. At the most time, if samples are not correlated, it is reasonable to assume the random data are stationary and can be represented by Gaussian distribution. This hypothesis is remarkably useful because many results and methods related to Gaussian distribution (such as propagation of uncertainty and least square parameter fitting) can be applied to data analysis. There are two types of data analysis: time-averaged analysis and spectral analysis. Time-averaged analysis will be used to estimate flow velocity, turbulence intensity and integral time scale. Spectral analysis can be used to provide information about how energy contained in the signal is distributed with respect to frequency. How to define sampling rate and sampling number is different for these two types of data analysis.

For time-averaged analysis, the sampling rate $SR$ is determined by integral time scale $T_1$. Under condition of uncorrelated samples, the sampling time between two consecutive samples is at least two times longer than the integral time scale of the velocity fluctuation. The requirement of the sampling rate $SR$ can be written as (Jorgensen, 2002):

$$SR \leq \frac{1}{2T_1}$$  \hspace{1cm} (3.5)

and

$$T_1 = \int_0^\infty \rho_x(\tau) \, d\tau$$  \hspace{1cm} (3.6)

where $\rho_x(\tau)$ is the auto-correlation coefficient of the samples which is defined as

$$\rho_x(\tau) = \frac{R_x(\tau)}{R_x(0)}$$  \hspace{1cm} (3.7)

where $R_x(\tau)$ is the auto-correlation function, i.e.
where $x(t)$ is a long time series sampled according to the Nyquist criteria.

For spectral analysis, the sampling rate $SR$ is defined as:

$$SR = 2 \times f_{\text{cut-off}}$$

(3.9)

where $f_{\text{cut-off}}$ is the cut-off frequency of a low pass filter. In the case of hot-wire anemometry, the default cut-off frequency is 10 kHz. Then, by using the fast Fourier transform (FFT), the sampled time domain data will be transformed to the frequency domain. The energy density spectrum is determined by applying FFT to velocity signal. As the mean velocity and the energy density are known, the integral length scale can be calculated.

3.3 Software for Instrumentation Application

The National Instruments® data acquisition system collects sensor data and transfers them to the computer through a USB port. In the computer, the transferred sampling data are recorded by software in terms of analog voltage. In practice, the sampling rate is up to 80 kHz and the sampling time is 20s or more. They vary according to different experimental purposes. The sampling number might be more than 1.6 M, which is a huge data set. If there is no software to serve as a tool to reduce the data, the time cost of data reduction will be very high. Therefore, a software has been developed, as part of the thesis work, to combine the data acquisition and reduction function together. Undoubtedly, LabVIEW® is the ideal development environment for this application.

NI LabVIEW® is a dataflow programming language. It is also called a graphical language. It consists of two parts: Front Panel and Graphical Block Diagram. The front
panel is built using controls and indicators. Controls are inputs, i.e. the supply data. Indicators are outputs, i.e. the indicate, or display, which are the results based on the inputs. The graphical block diagram contains the graphical source code. All of the objects placed in the front panel will appear in the graphical block diagram as terminals or function nodes. These function nodes are connected by drawing wires. The wires propagate variables and any node can execute as soon as all its input data become available. That means functions perform operations on controls and supply data to indicators by wires. A virtual instrument (VI) can be built by using function nodes and wires. A VI can either be run as a program, with the front panel serving as a graphical user interface (GUI), or, when dropped as a node onto the block diagram. This implies that each VI can be easily tested before being embedded as a subroutine into a larger program.

![GUI State Chart](image)

Figure 3.17 State chart

Considering the needs of the turbulent flow measurement, the State Machine technology is used to develop our own DAQ program, as shown in Figure 3.17. The GUI is a
state machine. When the program starts, it imports an initial file to reset all controllers and indicators. After initialization is done, the program jumps to the waiting state to be ready for response to user events. As shown in Figure 3.18, the user events include NEW, OPEN, and QUIT.

![WindSpeed DAQ System](image)

Figure 3.18 Main GUI

For data acquisition, the NEW button will be pressed down, and the main program will dynamically call a sub program- the data acquisition program. The main GUI vanished and the sub GUI shown in Figure 3.19 appears.

![Data acquisition GUI](image)

Figure 3.19 Data acquisition GUI
The data acquisition program is a state machine too. It will be waiting for response to user events. There are four buttons: SETTING, TEST, EXIT, and EMERGENCY; and four graphical indicators: Velocity, Turbulence Intensity, voltage time series (HWA), voltage time series (Pitot static tube). Click the SETTING button will setup the ambient and sampling parameters, as shown in Figure 3.20.

![Figure 3.20 Use SETTING button to setup the ambient and sampling parameters](image)

The surrounding ambient parameters include the dry temperature, the wet temperature, and the pressure. These three parameters will be used to calculate air density, which is an important parameter to correct the wind speed when Pitot static tube is used to measure flow velocity. The sampling parameters include the sampling rate and time. Click OK will finish all the initial setting and return to the data acquisition GUI. To click TEST, the testing position needs to be provided as input, as shown in Figure 3.21.

![Figure 3.21 TEST](image)
It is necessary to input the value so as to plot out the velocity and turbulence intensity instantaneously during the measurement. Again, click OK will return to the data acquisition GUI and the test starts. When the testing is done, the results can be exported manually. Click EMERGENCY on the data acquisition GUI can stop the test immediately. By clicking EXIT, the sub GUI will disappear and the main GUI will be activated.

Figure 3.22 Data reduction GUI
For data reduction, click OPEN button on the main GUI. The main GUI will disappear and the data reduction GUI shown in Figure 3.22 will appear. The data reduction program is also a state machine. It includes functions of auto-correlation, time-series, and PSD.

To do reduction analysis, an archive file will be opened first. Then select a probe (Pitot static tube or HWA). Finally, find out a point of interest and click Reduction button. The results will be plotted on the graphical indicators. If the results are acceptable, you can export them manually. To click STOP button will return to Main GUI. To click QUIT button on Main GUI, the main program will be closed and exit to Windows.

So far, the developed DAQ program works well. It is stable, robust and considerably saves experimental time. It is the foundation to complete the turbulent flow measurement in time.
CHAPTER 4 FLOW QUALITY OF EMPTY WIND TUNNEL

The CFI wind tunnel is a new facility. Before simulation of atmospheric boundary layer can be carried out, evaluation of flow quality in the empty wind tunnel is an essential step. The variation of the streamwise mean wind velocity along the vertical and horizontal directions in a plane normal to the flow direction at the middle of the turn table will be measured so that the uniformity and symmetry of the flow field can be evaluated. Flow in an empty wind tunnel should have low turbulence intensity. If the sampled signal manifests deviations larger than the range of uncertainty of a standard DAQ system, there must exist some noise sources which distort the signal. Thus, data treatment technique needs to be applied to remove noises.

4.1 Wind Tunnel Speed Range

The flow in the wind tunnel is generated by an axial flow fan (60W725 VW, supplied by Ironross in Sarnia, ON) with a power of 110 kw, and the rotation of the fan can be adjusted with a motor controller, the VACON control drive. It is a variable-frequency drive such that different input frequencies are related to different motor rotations. Determine the relation between the input motor frequency and the generated flow speed is the first step for operating a wind tunnel.

A probe, first Pitot static tube, then hot-wire anemometer (HWA), is placed at the center of the test section, which locates at the middle of the turn table and normal to the oncoming flow. Gradually increase the motor frequency from 10 Hz to 60 Hz with an increment of 10 Hz. Wind speed is measured at each motor frequency. Repeat this set of tests 11 times and the results are shown in Figure 4.1. It can be observed from the figure that the
relation between the motor frequency and the generated wind speed is linear. By applying
linear regression, it yields

\[ U = 0.25 f_m \] (4.1)

with the coefficient of determination \( R^2 \) being 0.9982, where \( U \) is the wind speed in the
wind tunnel, and \( f_m \) is the motor frequency. Since the maximum motor frequency is 60 Hz,
the maximum achievable wind speed in the empty wind tunnel is 15 m/s.

![Graph](image)

Figure 4.1 Relation between fan motor frequency and generated mean wind velocity

### 4.2 Measurement in Empty Wind Tunnel

To evaluate the flow quality in the empty wind tunnel, typical flow characteristics,
such as vertical and horizontal variation of mean wind speed, as well as turbulence intensity,
are measured. Pitot static tube is ideally suited for measuring mean wind speed because it is
insensitive to the high frequency components in the flow. Hot-wire anemometer can offer
very high spatial resolution and excellent frequency response characteristics, so it is used to measure turbulence intensity of the flow. To begin the measurement, a coordinate system is defined first.

4.2.1 Coordinate system and measurement planes

The definition of the coordinate system is shown in Figure 4.2. The X-axis is along the longitudinal direction of the tunnel and coincides with the oncoming flow direction, the Y-axis is in horizontal and normal to the flow direction, and the Z-axis is along the vertical direction. The origin is at the center of the vertical plane which itself is located at the middle of the turn table and perpendicular to the flow direction. The projection of the coordinate system origin on the tunnel floor coincides with the center of the turn table.

Figure 4.2 Definition of the coordinate system
To test wind speed velocity profiles, five measurement planes are chosen respectively for the horizontal and the vertical directions. The horizontal distribution of mean wind speed is measured in five different horizontal planes. They are parallel with each other and located at \( Z = -300 \text{ mm}, \ -150 \text{ mm}, \ 0 \text{ mm}, \ 150 \text{ mm}, \ 300 \text{ mm} \), as shown in Figure 4.3. Within each horizontal plane, the measurement is conducted along the \( Y \)-axis from \( Y = -900 \text{ mm} \) to \( Y = 300 \text{ mm} \) where the traverse Nut-\( Y \) reaches the maximum stroke. The spacing between two adjacent sampling locations is taken as 25.4 mm (1 in.) within the boundary layer close to the tunnel wall whereas 50.8 mm (2 in.) in the free stream.

\[
\begin{array}{c|c|c|c|c|c}
\text{Z (mm)} & \text{Y (mm)} \\
300 & -900 \\
150 & -150 \\
0 & 0 \\
-150 & 300 \\
-300 & 300 \\
\end{array}
\]

A probe moves along the direction of the arrow

Figure 4.3 Locations of test planes along Z-axis
Five vertical testing planes are chosen. They are located at $Y=-300$ mm, -150 mm, 0 mm, 150 mm, 300 mm, of which the tunnel vertical velocity profile is measured within each one of them, as shown schematically in Figure 4.4. When measuring the vertical profile of the mean wind speed in each vertical plane, the traverse moves from $Z=-900$ mm to $Z=300$ mm where the traverse Nut-Z reaches the maximum stroke. Within the boundary layer close to the tunnel floor, the spacing between two adjacent measuring points is 25.4 mm (1 in.), whereas beyond the boundary layer, it is taken as 50.8 mm (2 in.).

![Figure 4.4 Locations of test planes along Y-axis](image)

A probe moves along the direction of the arrow
4.2.2 Horizontal profiles of streamwise wind speed

A Pitot static tube (Dwyer® 160E-01) is mounted on the traverse Nut and used to test the horizontal profile of streamwise wind speed first. The motor frequency is set up at 48 Hz and the estimated streamwise wind speed based on Eq. (4.1) is 12 m/s. The sampling frequency is 128 Hz and the sampling time is 10 s. The test planes are chosen as shown in Figure 4.3. The signals are recorded and treated by the developed Labview program described in Chapter 3. The test results are shown in Figure 4.5. As can be seen, the horizontal profiles of the tunnel mean streamwise wind speed measured at five different vertical locations coincide well with each other. Based on the mean streamwise wind speed distribution pattern, the streamwise wind speed of 11.4 m/s at Y=-700 mm is 99% of the streamwise wind speed in the free stream, which is 11.6 m/s. Since the wind tunnel wall is at Y=-900 mm, the thickness of the boundary layer is thus estimated to be 200 mm. The five horizontal profiles of streamwise wind speed have the same pattern and the maximum difference between the data points sampled at the same Y location is less than 0.2 m/s, i.e. less than 1.7% of the free stream wind speed, which suggests that the flow field in the empty wind tunnel has a good uniformity and symmetry in the vertical direction. However, in the range from Y=-300 mm to 0 mm, a “bump” is observed on all five horizontal velocity profile curves at Y=-100 mm where the wind speed is obviously slightly lower than those sampled at other locations in the freestream. The discrepancy is about 0.5 m/s, i.e. 4.3% of the freestream velocity. This is not acceptable. To find out the cause, HWA is used to repeat these measurements.
A sensitivity analysis has been conducted to determine the optimum sampling frequency and time for the hot-wire measurement. In the current study, the sampling frequency of hot-wire measurement is taken as 32 kHz, which is more than the low-pass filter cut-off frequency of 10 kHz and less than the frequency based on the unrelated sampling time of 0.0089 ms, i.e. $1/(2 \times 0.0089)=56$ kHz. Based on the results shown in Figure 4.6 and 4.7, the optimum sampling number at sampling frequency of 32 kHz is $2.56 \times 10^6$. Thus, the sampling time used for hot-wire measurement is chosen to be 80 s.
Figure 4.6 Minimum required sampling number for mean wind speed at sampling frequency of 32 kHz

Figure 4.7 Minimum required sampling number for $\sigma$ of mean wind speed at sampling frequency of 32 kHz
Figure 4.8 shows the horizontal wind velocity profile measured by hot-wire at X=0 and Z=0. The same pattern as that obtained by the Pitot static tube measurement in Figure 4.5 can be observed, where a “bump” exists in the vicinity of Y=-100 mm.

After numerous trials and investigations, the reason why there is always a “bump” appears in the horizontal velocity profile at Y=-100mm is found. The traverse system is a two-axis motion system. Each axis is 1600 mm long and 90 mm wide with the frontal area against wind being 0.144 m$^2$. So the blockage ratio of the traverse system is 8.7%. Thus, the blockage effect of the traverse system is not negligible. The probes are mounted on the traverse system during the tests. Although a Z-shaped rod (shown in Figure 3.11) is used to avoid this kind of problem in advance, it is possible that the testing results are still affected by the presence of the traverse system. As shown schematically in Figure 4.9, during tests,
the traverse vertical shaft moves from the door side of the tunnel to the window side. Therefore, the flow field between the traverse vertical shaft and the window side will change with the movement of the traverse vertical shaft.

![Diagram of traverse vertical shaft movement and setup of the Z-shaped rod](image)

**Figure 4.9** Schematics of traverse vertical shaft movement and setup of the Z-shaped rod

If the probe happens to locate in the influence zone, the test results will not represent the real wind speed in freestream. This is a reasonable hypothesis why there is a “bump” at $Y=150$ mm. To verify this, the orientation of the Z-shaped rod is adjusted so that the HWA is placed in front of the center line of the traverse vertical axis and parallel to the flow direction as shown in Figure 4.10.
The horizontal profile of streamwise wind speed at X=0 and Z=0 measured using adjusted orientation of the Z-shaped rod is plotted in Figure 4.11.

Figure 4.10 Schematics of the adjusted installation of Z-shaped rod and HWA

Figure 4.11 Horizontal profile of velocity after adjustment of Z-rod orientation (X=0, Z=0)
The mean velocity of the profile is 10.5 m/s, which is less than the predicted freestream velocity of 12 m/s. As shown in Figures 4.9 and 4.10, there is a velocity gradient along the streamline in the stagnation plane. The testing results suggest that the position of the HWA is still within the influence zone of the traverse vertical shaft. However, at the same time, the horizontal profile in Figure 4.11 shows no “bump” at Y=-100 mm, which proves that the presence of the traverse system will disturb the testing results if the probe is placed in the influence zone. It is worth mentioning that this problem was resolved lately after all measurements within the scope of the current study have been completed. Thus, the HWA results presented in the remaining document are still based on the original Z-shaped rod set up in Figure 4.9. A new probe support needs to be designed so that the position of the probe would be beyond the traverse shaft influence zone.

4.2.3 Vertical profiles of streamwise wind speed

The Pitot static tube is used to measure the vertical profile of streamwise wind speed. The five testing planes are shown in Figure 4.4. The sampling frequency is 128 Hz, and the sampling time is 10 s. The testing results are shown in Figure 4.12. It is observed that the vertical profiles of streamwise wind speed measured at five different horizontal locations of Y=-300 mm, -150 mm, 0 mm, 150 mm and 300 mm agree well except the one at Y=-150 mm gives slightly lower value. This is believed to be caused by the same reason for the “bump” in the horizontal profiles as explained in Section 4.2.2. Otherwise, the horizontal uniformity and symmetry of the flow field in the empty wind tunnel can be clearly observed from Figure 4.12.
Similar to what has been done for the horizontal profile of streamwise wind speed measurements, the hot-wire anemometer is used to repeat the measurements with a sampling frequency of 32 kHz and a sampling time of 80 s. The measured vertical profiles of streamwise wind speed at the five selected horizontal locations are shown in Figure 4.13. This set of results agrees very well with those in Figure 4.12 by Pitot static tube measurement.

![Figure 4.12 Vertical profiles of streamwise wind speed (Pitot static tube) (X=0)](image-url)
4.2.4 Turbulence intensity

Turbulence intensity is another important flow characteristic to evaluate the quality of the wind tunnel. Hot-wire anemometer is used to measure the turbulence intensity of the CFI wind tunnel. The results of the turbulence intensity variation along the vertical direction at X=0, Y=0 and along the horizontal direction at X=0, Z=0 are presented respectively in Figures 4.14 and 4.15. Results show that the turbulence intensity in the freestream along the vertical direction is about 4% and that close to the tunnel floor is about 29%. The same phenomenon appears in the Horizontal profiles of turbulence intensity shown in Figure 4.15. In freestream, the horizontal turbulence intensity varies around 4%, whereas within the boundary layer close to the tunnel wall, the turbulence intensity increases up to 10%. This level of turbulence intensity is not reasonable for an empty wind tunnel.
Appar-ently, neither the vertical nor the Horizontal profiles of turbulence intensity reflects the actual turbulence level of the flow field in the empty wind tunnel. There ap-
pears to be some unknown noise sources which may exist in the wind tunnel structure itself, or the ambient environment, or the DAQ system. These noises could cover the useful signals and distort the actual turbulence intensity in the freestream. The spatial resolution of the HWA could thus be reduced so that the fine structure of the turbulent flow could not be correctly detected.

4.2.5 Identification of noise sources

To identify the potential noise sources, it is necessary to analyze signals taken by the DAQ system. Conducting power spectrum analysis is an effective way to find out the possible noise sources. Figure 4.16 is a segment of sample wind speed PSD. The sampling frequency is 1024 Hz, which is the same as the cut-off frequency of the low-pass filter embedded in the anemometer. The sampling time is 10 s. As shown in Figure 4.16, numerous low frequency components can be seen in the PSD. Usually, these low frequency components represent noises from mechanical vibration, signal interference between cables, or static pressure fluctuation. All these possibilities are then examined one by one.

![Figure 4.16 A segment of sample wind speed PSD](image)

- Mechanical vibration
The fan motor in the wind tunnel is the major source to cause mechanical vibration during the tunnel operation. To find out if the fan motor operation would distort the HWA signal, an accelerometer is used to measure the mechanical vibration of the tunnel during its operation. Two locations, Location A and Location B, as shown in Figure 4.17 and Figure 4.18, are chosen for the installation of an accelerometer. Location A is on the exterior surface of the fan house wall close to the fan motor and Location B is on the frame under the wind tunnel door.

![Figure 4.17 Location A](image1)

![Figure 4.18 Location B](image2)

After turning on the fan motor, its frequency is adjusted gradually from 10 Hz to 60 Hz with an interval of 10 Hz. At each fan frequency, the acceleration of the tunnel wall at
Location A and Location B are measured. The results are listed in Table 4.1. The ratio between the accelerations at Location A and Location B shows that the vibration caused by the fan motor operation at Location B is significantly weaker than that at Location A and thus mechanical vibration would have a trivial role in distorting HWA signal. This is because a flexible connector has been designed and installed between the fan house and the test section of the tunnel for vibration isolation, as shown in Figure 4.19.

Table 4.1 Accelerations at different locations and motor frequencies

<table>
<thead>
<tr>
<th>Motor Frequency (Hz)</th>
<th>Acceleration (m/s²)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Location A</td>
<td>Location B</td>
</tr>
<tr>
<td>10</td>
<td>4.72</td>
<td>0.32</td>
</tr>
<tr>
<td>20</td>
<td>2.41</td>
<td>0.45</td>
</tr>
<tr>
<td>30</td>
<td>4.07</td>
<td>0.31</td>
</tr>
<tr>
<td>40</td>
<td>5.14</td>
<td>0.61</td>
</tr>
<tr>
<td>50</td>
<td>5.29</td>
<td>0.68</td>
</tr>
<tr>
<td>60</td>
<td>4.54</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Figure 4.19 Flexible connector between the fan house and the test section
b) Signal interference between cables

A four-core data cable (“1” in Figure 4.20) is used to connect the Pitot static tube and the hot-wire anemometer to NI 9222, as shown in Figure 4.20. The BNC cable (“2” in Figure 4.20) connects to the hot-wire anemometer and another four-core cable (“3” in Figure 4.20) to the Pitot static tube. Although all these three cables are covered by aluminum foil shielding layer, no shielding layer is provided at the intersection point of the cables which could cause signal interference.

To fix the problem, these three cables are replaced by two separate cables. A BNC cable directly connects the hot-wire anemometer to NI 9222 and a four-core cable connects the Pitot static tube to NI 9222. The turbulence intensity measurement is repeated after the rearrangement of the wires. Results show that the freestream turbulence intensity decreases from 4% to 2.5%.

Besides, there are two power cables connecting the traverse motor with the drive. One is a single cable and the second consists of three shorter cables connected together. However, the two connection points between the shorter cables on the second power cable
are not provided with any shielding layers. After covering them with aluminum foil, the turbulence intensity is found to slightly reduce to 2.2%. To identify potential electromagnetic compatibility (EMC) emission of the cables, the second power cable is disconnected which results in a decrease of the turbulence intensity to 1.2%. When the first power cable is also disconnected, the turbulence intensity is further reduced to 0.8%. At present, the sources in these two power cables where the electromagnetic energy emission occurs still cannot be clearly identified due to lack of some special testing devices. Therefore, a temporary solution at the moment is to turn off the power of the traverse system after it moves to the designated position during test. In practice, this approach ensures to obtain better testing results despite the traverse system has to be operated manually.

c) Fluctuation of static pressure in the wind tunnel

In a low speed wind tunnel, air flows along streamlines and the flow is assumed to be steady, incompressible, and frictionless. According to the Bernoulli’s principle, the wind speed in the tunnel is determined by the dynamic pressure. The static pressure in the tunnel is fluctuating when the tunnel is running whereas the total pressure is a constant. The fluctuation of the static pressure will cause the variation of the dynamic pressure and thus the wind speed at a low frequency as shown in Figure 4.21. If the sampling time is long enough, the effect of the static pressure variation on the mean velocity will become negligible. However, the fluctuation of static pressure is always included in the calculation of turbulence intensity. In the time domain analysis, a filter will typically be applied to remove this kind of low frequency component. One of the challenges is how to design a filter with
minimum frequency leakage. In the current study, a new method is developed to take care of this issue. The unrelated sampling time is determined first by conducting autocorrelation analysis. Then, the sampled mean velocity time history is divided into many short time series, the length of which is longer than the unrelated sampling time. Within each short time series, a segment of mean velocity time history having the same length as the unrelated sampling time is randomly chosen and its standard deviation is calculated. This is repeated for all the randomly selected segments within each short time series. The repeating time is determined based on the sampling time and rate. The turbulence intensity is equal to the ratio between the mean value of all the standard deviations and the mean wind speed based on the original complete time series. This approach can not only effectively eliminate the influence of the static pressure fluctuation contained in the raw signal but also avoid introducing additional errors. By applying such a data treatment technique, the turbulence intensity decreases to 0.17%. This approach has been implemented in code (please refer to Appendix B) and added to the developed Labview program described in Chapter 3.

Figure 4.21 Mean wind speed oscillates at a low frequency
d) Final results of the turbulence intensity

After all the above noise sources have been identified and eliminated, a series of experiments are carried out again. The vertical and horizontal profiles of turbulence intensity are shown in Figure 4.22 and Figure 4.23, respectively. It can be seen from both figures that the turbulence intensity in the freestream is 0.17%. The fluctuation in the freestream turbulence intensity observed in Figure 4.14 and Figure 4.15 disappears. The distribution of the turbulence intensity is much more stable with no randomly scattered points. As shown in Figures 4.22 and 4.23 that the turbulence intensity starts to increase at $Z=-700$ mm or $Y=200$ mm, respectively, suggesting that the boundary layer thickness of the empty wind tunnel is 200mm. This is consistent with the value obtained from the wind speed profile shown in Figure 4.8 and Figure 4.13.

![Figure 4.22 Vertical profile of turbulence intensity (X=0)]
According to the relation between the fan motor frequency and the generated wind speed shown in Figure 4.1, the wind speed in the wind tunnel varies linearly with the frequency of the fan motor and equals to 0.25 times of it. Since the maximum motor frequency is 60 Hz, the maximum achievable wind speed in the CFI wind tunnel is 15 m/s. Three types of potential noise sources have been examined. They include the mechanical vibration due to fan motor operation, the signal interference between instrumentation cables, and the static pressure fluctuation in the empty wind tunnel, with the latter two being identified as the major sources of noise contained in the raw signal of hot-wire measurement data. After eliminating these noises, the freestream turbulence intensity of the empty wind tunnel is 0.17%, which meets the requirement for a low speed empty wind tunnel.
To evaluate the horizontal uniformity and symmetry of the flow field in the testing section, the profiles of mean wind speed and turbulence intensity have been measured at five different horizontal planes located at Z= -300 mm, -150 mm, 0 mm, 150 mm, and 300 mm. Similarly, the profiles of mean wind speed and turbulence intensity have also been measured in five vertical planes at Y= -300 mm, -150 mm, 0 mm, 150 mm, and 300 mm to check the vertical uniformity and symmetry of the flow field. Results show that the five horizontal or vertical profiles of streamwise wind speed agreed respectively with each other, which manifests the uniformity of the flow field. In the freestream, the horizontal or vertical profiles are symmetric about the middle plane. The patterns of the mean wind speed profiles and turbulence intensity profiles depict that the boundary layer thickness of the empty wind tunnel is 200 mm.

Based on the empty wind tunnel measurement results, the CFI wind tunnel can reach a maximum wind speed of 15m/s. The flow field at the test section is uniform and symmetric with a low turbulence intensity of 0.17%. These suggest that the flow quality in the empty CFI wind tunnel is satisfactory and the facility is suitable to be used for various wind-related researches.
CHAPTER 5 FLOW CHARACTERISTICS IN WIND TUNNEL WITH
THE ADDTION OF PASSIVE DEVICES

5.1 Design of Passive Devices

Various types of passive devices are typically used as eddy generators to simulate atmospheric boundary layer in a wind tunnel. The Counihan method (Counihan, 1969) and the Standen method (Standen, 1972) are usually used to design spires as eddy generators. The spires designed by the Counihan method have triangular, cranked triangular, plane elliptic and elliptic wedge shapes. Because of the complicated geometric shape and uncertain effects of the barriers on flow, it is not easy to design spires according to the Counihan method. Nevertheless, this approach is still widely used to predict wind properties in urban environment. In the Standen method, the geometric shape of spires is much simpler. Standen compared the simulation results by different researchers using spires of different shapes and found there was hardly any evidence to show the advantage of using a more complex spire shape than the triangular one. Irwin further developed Standen’s idea and proposed a physical model (Irwin, 1979), as shown schematically in Figure 5.1. In this model, the spire shape was assumed to be triangular and the Principle of Conservation of Momentum was applied to derive design formulae. This set of formulae provided a convenient tool for spire design to satisfy different flow simulation requirements. At present, Irwin's method is the most popular approach used by different wind tunnel labs in simulating atmospheric boundary layer. It is also used in the current study for spire design.
5.1.1 Design of spires

The spire shape is designed to achieve the desired atmospheric boundary layer thickness corresponding to a particular value of $\alpha$ in the power law velocity profile for a certain terrain type. It should give acceptable lateral uniformity of the mean velocity profile at a distance approximately six spire heights downstream of the spires. To maintain maximum lateral uniformity of flow in a wind tunnel, the first step is to arrange the spire array symmetrically at the inlet of the working section. Based on the suggestion by Irwin, the spires are placed with a lateral spacing of half spire height, i.e.

$$\text{Spire lateral spacing} = \frac{d}{N_s} = \frac{h}{2}$$  \hspace{1cm} (5.1)

where $d$ is the width of the wind tunnel test section, $N_s$ is the number of spires $N_s=3, 4, 5...$, and $h$ is the spire height.

The boundary layer thickness generated by spires in a wind tunnel is given as follows

$$\delta = 0.72(1 + 0.5\alpha)h$$  \hspace{1cm} (5.2)

where $\delta$ is the thickness of the generated boundary layer, $\alpha$ is the exponent in the power law wind velocity profile, and $h$ is the spire height.

Based on Eq. (5.2), the maximum thickness of boundary layer generated by spires in a wind tunnel can be determined. For example, if assume $N_s = 3, \alpha = 0.33$ and $d = 1.8 \text{ m}$, then from Eq. (5.1), the spire height is $h=1.2 \text{ m}$. Thus, the generated boundary layer thickness is

$$\delta = 0.72(1 + 0.5 \times 0.33) \times 1.2 = 1\text{ m}$$

In the Irwin’s method, the working section of a wind tunnel is defined as a control
volume, as shown schematically in Figure 5.1. The desired wind velocity profile at a distance approximately six spire heights downstream of the spires is assumed to have the form of

\[
\frac{U(z)}{U_\delta} = \left(\frac{z}{\delta}\right)^{\alpha}
\]  \hspace{1cm} (5.3)

where \(U(z)\) is the mean wind velocity at height \(z\), \(U_\delta\) is the mean wind velocity at the boundary layer height \(\delta\), \(z\) is the height above the wind tunnel floor, and \(\delta\) is the boundary layer thickness.

![Figure 5.1 Rectangular working sections as a control volume (after Irwin, 1979)](image)

Based on the Principle of Conservation of Momentum, the required total frontal area of all spires is (Irwin, 1979):

\[
A_s = \frac{\psi H d}{(1 + \psi \theta) C_{D_s}}
\]  \hspace{1cm} (5.4)

where \(A_s\) is the total frontal area of all spires, \(H\) is the height of the wind tunnel test section, \(\theta\) is the blockage factor (usually \(1 < \theta < 2.8\) and \(\theta = 1.7\) for three spires), and \(C_{D_s}\) is the drag coefficient of each spire (\(C_{D_s} = 1.45\) for three spires). The coefficient \(\psi\) can be computed from
\[
\psi = \beta \left( \frac{2}{1+2\alpha} + \beta - C_f \frac{X_0}{\delta} \frac{1+\alpha}{\alpha} \right)/(1 - \beta)^2 \tag{5.5}
\]

where \( \beta = \frac{\delta}{H} \frac{\alpha}{1+\alpha} \). \( C_f \) is an effective surface friction coefficient, \( X_0 \) is the distance between station 2 and station 3 in Figure 5.1, which is about \( 4h \) to \( 6h \). When \( C_f \) is given as an approximate relation between the local skin friction coefficient and \( \alpha \), it has the form of

\[
C_f = 0.136\left( \frac{\alpha}{1+\alpha} \right)^2 \tag{5.6}
\]

Substitution of Eq. (5.6) into Eq. (5.5) leads to

\[
\psi = \beta \left( \frac{2}{1+2\alpha} + \beta - \frac{X_0}{\delta} \frac{0.136\alpha}{1+\alpha} \right)/(1 - \beta)^2 \tag{5.7}
\]

The spire may be in any roughly triangular shape. From Eqs. (5.1) and (5.4), the base of the triangle has a dimension of

\[
b = \frac{\delta H}{(1+\psi\theta)C_D_0} \tag{5.8}
\]

The current study aims at using three spires \((N_s = 3)\) to simulate atmospheric boundary layer associated with terrain condition of Exposure A, i.e. \( \alpha = 0.33 \). The height and width of the CFI wind tunnel test section are both 1.8m. The required spire height can be determined from Eq.(5.1), which is

\[
\frac{h}{N_s} = \frac{2d}{\delta H} = \frac{2 \times 1.8}{3} = 1.2 \text{ (m)}
\]

From Eq. (5.2), the thickness of the generated boundary layer is

\[
\delta = 0.72(1 + 0.5\alpha)h = 0.72(1 + 0.5 \times 0.33) \times 1.2 = 1 \text{ (m)}
\]

The parameter \( \beta \) in Eq. (5.5) is

\[
\beta = \frac{\delta}{H} \frac{\alpha}{1+\alpha} = \frac{1}{1.81+0.33} = 0.138
\]

Set \( X_0 = 6h = 7.2 \text{ (m)} \), the parameter \( \psi \) in Eq. (5.5) can be computed, which is
\[ \psi = \beta \left( \frac{2}{1+2\alpha} + \beta - \frac{x_0 0.136\alpha}{\delta} \frac{1}{1+\alpha} \right)/(1 - \beta)^2 = 0.2064. \] The frontal area of all spires can be determined from Eq. (5.4), i.e.

\[ A_s = 0.3414 \text{ (m}^2\text{)} \]

Finally, the spire base can be determined using Eq. (5.8), which gives

\[ b = 0.19 \text{ (m)} \]

So, the wooden spires are designed to have a triangular shape with a height of 1.2 m and a base of 0.19 m, as illustrated in Figure 5.2. The thickness of the spires is designed to be 20 mm. They will be arranged symmetrically at the inlet of the wind tunnel test section with a center-to-center lateral spacing of 0.6 m, and the spacing between the center of the side spire to the wind tunnel wall is 0.3 m.

Figure 5.2 Wooden triangular spire (mm)
5.1.2 Design of roughness elements

The roughness elements are usually used together with spires to make corrections for the wind velocity profile generated by spires to satisfy the atmospheric boundary layer simulation requirement associated with a certain type of terrain condition in the wind tunnel. There are no common formulae for designing roughness elements. Many researchers suggested that the height of a cubic roughness element should be in the range of \(\frac{\delta}{16}\) to \((h - \delta)\), where \(h\) is the spire height and \(\delta\) is the thickness of the generated boundary layer in the wind tunnel. In the current project, the height of the cubic roughness element is designed to be \(\frac{\delta}{16} \approx 60 \text{ (mm)}\).

To secure roughness elements in the designated location during tests, a thin layer of steel sheet with a thickness of 0.76 mm is placed on the wind tunnel floor in the test section. Two magnets, D43-N52 supplied by K&J Magnetics Inc., are installed at two diagonal corners on the bottom surface of each cubic roughness element as shown in Figure 5.3. Each magnet has a diameter of 6.35 mm (1/4") and a thickness of 4.7625 mm (3/16"). The maximum pull force can be resisted is 3.71lbs. When place the roughness elements on the steel sheet, the magnetic force would ensure them to be in place even when subjected to the maximum wind speed of the tunnel.

5.1.3 Testing cases

In the following experiments, the spire-roughness-element technology will be applied to simulate the atmospheric boundary layer associated with Exposure A in the CFI wind tunnel. To properly understand the effect of different types of passive devices, the
experiments are designed to include the following cases: spires-only, roughness-elements-only, and spires combined with roughness elements. The profile of streamwise wind speed and turbulence intensity at the test section under different arrangement of passive devices will be studied and compared with those in the empty tunnel, so that the function of different types of passive device can be properly understood. For the cases of spires combined with roughness elements, the integral length scale and power spectrum of the flow field will also be analyzed.

**Figure 5.3 Bottom surface of a cubic roughness element with two magnets (mm)**

**5.2 Effect of spires on the flow characteristics**

To study the effect of spires on the characteristics of generated flow in the wind tunnel, the three spires designed in Section 5.1.1 are placed at the entrance of the wind tunnel testing section, as shown in Figure 5.4. They are placed symmetric about the $Y=0$ plane. The spacing between the center of the two adjacent spires is 600 mm, whereas the spacing between the center of the side spire and the tunnel wall is 300 mm. Based on the
Irwin’s approach, if the exponent \( \alpha \) in the power law wind speed profile is 0.33 (Exposure A) and the height of the spires is 1200 mm, the thickness of the generated boundary layer in the wind tunnel at a distance six times of spire height downstream of the spires should be 1000 mm. This will be verified in the testing.

![Figure 5.4 Three spires at the entrance of the wind tunnel test section](image)

First, the vertical profiles of streamwise wind speed in the empty wind tunnel and after installation of three spires are measured at \( X=0 \) and \( Y=0 \) under a fan motor frequency of 48 Hz. They are plotted in Figure 5.5. As can be seen from the figure, in the empty tunnel, a turning point appears on the vertical velocity profile at the height of 200 mm above the tunnel floor, beyond which the flow is in the freestream field with a stable speed in the vicinity of 12 m/s. However, after placing three spires at the tunnel entrance, the pattern of the vertical profile of streamwise wind speed changes drastically. Within the range of \( Z=-900 \) mm to -200 mm, the wind speed profile exhibits a shape of a power function. Be-
Beyond $Z=100$ mm, the wind speed remains at 12.2-12.3 m/s. There is a transition zone between $Z=-200$ mm to 100 mm where a slight increase of wind speed from 11.8 m/s to 12.2 m/s occurs. It seems that this set of data alone would not allow an accurate identification of the boundary layer thickness generated by the three spires.

Figure 5.5 Vertical profiles of streamwise wind speed in the empty wind tunnel and after installing three spires ($X=0$, $Y=0$)

On the other hand, Figure 5.6 gives the vertical profiles of turbulence intensity at the same measurement location of $X=0$ and $Y=0$ in the empty wind tunnel and the tunnel with three spires. A turning point can be observed from the latter at $Z=100$ mm. The turbulence intensity decreases gradually from 1% close to the tunnel floor to 0.26% at $Z=100$ mm, the trend of which matches the triangular shape of the spires. Beyond this height the turbulence intensity recovers to the same level as that of the empty tunnel and remains.
This clearly indicates that the thickness of the boundary layer generated by the three designed spires is 1000 mm, which agrees with the expected boundary layer thickness predicted by Eq. (5.2). This is a very important feature of the Irwin’s method. When simulating the natural atmospheric boundary layer associated with a specific terrain condition represented by the exponent \( \alpha \) in the corresponding power law wind velocity profile, the geometric scale used in the simulation is determined first, based on which the required thickness of the simulated boundary layer in the wind tunnel can be determined. Following this, the spire height to satisfy this simulation requirement can be calculated from Eq. (5.2) and spire base from Eq. (5.8). The results in Figures 5.5 and 5.6 prove that the current spire design according to the Irwin’s method is successful. It can generate a boundary layer with a thickness of 1 m in the CFI wind tunnel as desired.

![Image of turbulence intensity graph](image)

Figure 5.6 Vertical profiles of turbulence intensity in the empty wind tunnel and after installing three spires (X=0,Y=0)
To assess the symmetry and uniformity of the flow field at the test section after installing three spires, the vertical profiles of streamwise wind speed and vertical turbulence intensity in four other vertical planes along the X-axis, i.e. Y=-300 mm, -150 mm, 150 mm and 300 mm, are plotted respectively in Figures 5.7 and 5.8, along with those at Y=0. The agreement of all five curves in these two figures shows that with the current design and arrangement of spires, the generated flow field at the test section is uniform and symmetric.

![Figure 5.7 Vertical profiles of streamwise wind speed after installation of three spires](image)
Figure 5.8 Vertical profiles of turbulence intensity after installation of three spires

However, it is worth noting that although the spires can produce the desired boundary layer thickness, the resulted vertical wind velocity profile does not agree with a power law curve with an exponent of $\alpha=0.33$. Five dimensionless vertical profiles of streamwise wind speed measured at $X=0$ in five different testing planes of $Y=-300$ mm, -150 mm, 0 mm, 150 mm and 300 mm are portrayed in Figure 5.9, together with the power law wind velocity profile of $\alpha=0.33$. Results show that after the addition of three spires, although the vertical wind velocity profiles measured at five different $Y$ locations agree well with each other, the discrepancy between these curves and the theoretical power law curve of $\alpha=0.33$ can be clearly seen. Take the vertical wind velocity curve at $Y=0$ as an example, it can be fitted by a power law curve with an exponent of $\alpha=0.14$, as shown in Figure 5.10. To achieve a larger value of $\alpha$ as the power law exponent, roughness elements should be in-
roduced to cover the mixing zone downstream of the spires. The associated testing results will be presented in Section 5.4.

**Figure 5.9** Comparison of dimensionless vertical profiles of streamwise wind speed (X=0)

**Figure 5.10** Dimensionless wind speed fitting curve (X=0, Y=0)
To evaluate the horizontal flow symmetry and uniformity, the horizontal profiles of streamwise wind speed and turbulence intensity are measured in the horizontal plane of $Z=-700$ mm at $X=0$, as shown respectively in Figures 5.11 and 5.12. In the freestream, the velocity is 9.5 m/s, which is the same as that in the vertical profile of streamwise wind speed shown in Figure 5.7. The reason of the “bump” in the horizontal wind velocity profile at the same height in Figure 5.11 has been explained in Chapter 4. Otherwise, the horizontal uniformity and symmetry of the flow field can be clearly observed from the patterns of the curves in Figures 5.11 and 5.12.

Figure 5.11 Horizontal profile of streamwise wind speed (three-spires) ($X=0, Z=-700$ mm)
Figure 5.12 Horizontal profiles of turbulence intensity (three-spire) (X=0, Z=-700 mm)
5.3 Effect of roughness elements on flow characteristics

Before combining the application of roughness elements with spires, it is necessary to understand the presence of roughness elements alone in the wind tunnel on the characteristics of flow structure. In this section, the properties of the flow field at the test section when the upstream tunnel floor is covered by roughness elements will be measured. Three testing cases will be conducted, each associated with a different frontal area density of roughness elements computed according to Eq. (2.9). They are listed in Table 5.1.

Table 5.1 Three testing cases to study roughness elements effect

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Total pieces</th>
<th>Array</th>
<th>Frontal area density</th>
<th>Longitudinal spacing (mm)</th>
<th>Lateral spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>200</td>
<td>10x20</td>
<td>5.6%</td>
<td>360</td>
<td>180</td>
</tr>
<tr>
<td>Case 2</td>
<td>144</td>
<td>8x18</td>
<td>4%</td>
<td>400</td>
<td>225</td>
</tr>
<tr>
<td>Case 3</td>
<td>72</td>
<td>6x12</td>
<td>2%</td>
<td>600</td>
<td>300</td>
</tr>
</tbody>
</table>

For example, in case 1, the number of roughness element is 200 pieces, the cube is 60 mm × 60 mm × 60 mm. The frontal area of a cube is 60 mm×60 mm=3600 mm². The array of roughness elements is 10x20 and will cover a zone of 7200 mm long×1800 mm on the wind tunnel floor. So, the influence zone of each roughness element is 180 mm in the width (1800 mm/10=180 mm), 360 mm in the length (7200 mm/20=360 mm), and the area is 64800 mm². Then, according to Eq. (2.9),

\[ \bar{\lambda}_f = \frac{\bar{A}_f}{\bar{A}_T} = \frac{60 \times 60}{360 \times 180} = 0.056 \text{ or } 5.6\% \]

Figure 5.13 shows a sample layout of roughness element for Case 3, which requires 72 roughness elements with a frontal area density of 2%. For each testing case, the vertical
profile of streamwise wind speed and turbulence intensity profile at Y= -300 mm, Y= 0 mm, and Y= 300 mm are measured under fan motor frequency of 48 Hz. These results are shown in Figures 5.14 to 5.19.

Figure 5.13 Arrangement of roughness element (Case 3)

![Figure 5.13 Arrangement of roughness element (Case 3)](image)

Figure 5.14 Vertical profiles of streamwise wind speed with 200 pieces of roughness element (frontal area density of 5.5%) (X=0)

![Figure 5.14 Vertical profiles of streamwise wind speed with 200 pieces of roughness element (frontal area density of 5.5%) (X=0)](image)
Figure 5.15 Vertical profiles of turbulence intensity with 200 pieces of roughness element (frontal area density of 5.5%) (X=0)

Figure 5.16 Vertical profiles of streamwise wind speed with 144 Pieces of roughness element (frontal area density of 4%) (X=0)
Figure 5.17 Vertical profiles of turbulence intensity with 144 pieces of roughness element (frontal area density of 4%) (X=0)

Figure 5.18 Vertical profiles of streamwise wind speed with 72 Pieces of roughness element (frontal area density of 2%) (X=0)
Results in literature (Cheng and Castro, 2002) show that the thickness of the boundary layer downstream of the roughness element array is typically 2-5 times the height of the roughness element. In the current case, the height of the roughness elements is 60 mm, and the boundary layer thickness identified from Figures 5.14 to 5.19 for the three different roughness element layout cases are the same, which is 400 mm. It is roughly 6.5 times the height of the roughness elements.

For the convenience of comparison, the vertical profiles of streamwise wind speed and turbulence intensity at Y=0 in the three tested roughness elements cases are shown together with those of the empty tunnel case in Figures 5.20 and 5.21. It can be observed from these two figures that beyond the boundary layer, the turbulence intensity becomes the same as that in the empty tunnel and remains as a constant, whereas the wind speed is slightly lower than that in the empty tunnel but also remains the same along the vertical di-
rection.

Figure 5.20 Comparison of vertical profiles of streamwise wind speed (empty tunnel v.s. three roughness-element-only cases, X=0, Y=0)

Figure 5.21 Comparison of turbulence intensity profiles (empty v.s. three roughness-element-only cases, X=0, Y=0)
5.4 Combined effect of spires and roughness elements on flow characteristics

Three cases will be tested to study the flow characteristics at the test section when spires and roughness elements are used together to simulate atmospheric boundary layer in the CFI wind tunnel. In all these cases, the three spires will be placed at the entrance of the wind tunnel test section as described in Section 5.2, whereas the frontal area density and layout of the roughness elements will be changed according to the three cases studied in Section 5.3. Figure 5.22 shows a schematic layout of using three spires combined with 200 cubic roughness elements. The array of roughness elements is 10x20, i.e. 10 pieces per row and 20 rows in total. Figure 5.23 gives an actual layout of spires combined with roughness elements in the CFI wind tunnel during the tests.

Figure 5.22 Schematic layout of using spires combined with roughness elements to simulate atmospheric boundary layer in wind tunnel (mm)
The spire-roughness-element technique, shown in Figures 5.22 and 5.23, has been proved as a simple and effective method to generate a thick boundary layer in the wind tunnel. The method is capable of producing a wind speed profile with a wide range of boundary layer associated with different terrain types. The spire shape, typically triangular, can be designed to generate certain thickness of boundary layer associated with a specific type of terrain condition. The roughness elements are then added. By adjusting the frontal area density of roughness elements, the so generated vertical profile of streamwise wind speed can be corrected to match the $\alpha$ exponent in the power law velocity profile for this terrain type. It is very possible that a certain relation exists between the frontal area density of roughness elements and the exponent $\alpha$ of the power law velocity profile. This hypothesis will be examined in the current study.

Figure 5.23 Actual layout of three spires combined with 200 roughness elements in the CFI wind tunnel
5.4.1 Three spires with 72 pieces of roughness elements (2\% frontal area density)

Figures 5.24 and 5.25 show the vertical profiles of streamwise wind speed and the turbulence intensity in the testing plane of $Y=0$ at $X=0$ respectively. The fan motor frequency is at 48 Hz. The wind speed in the freestream is about 12.06 m/s and the thickness of the boundary layer is determined by checking the turning point in the turbulence intensity profile, which is 1000 mm. Figure 5.26 depicts the dimensionless vertical profile of streamwise wind speed. The exponent $\alpha$ of the power law wind speed profile fitting curve is 0.1397, which is slightly higher than $\alpha=0.14$ in the spire-only case. The turbulence intensity in the freestream is 0.206\% and its shape within the boundary layer is also close to a power function curve. The horizontal profile of streamwise wind speed and the horizontal profiles of turbulence intensity measured in the horizontal plane of $Z=-400$ mm at $X=0$ are shown respectively in Figure 5.27 and 5.28. The wind speed is 11.63 m/s in the freestream which nearly equals to 11.36 m/s in the empty tunnel case. The freestream turbulence intensity is 0.75\%, which is higher than 0.17\% in the empty tunnel case.
Figure 5.24 Vertical profile of streamwise wind speed (three spires with 72 pieces of roughness elements, X=0, Y=0)

Figure 5.25 Vertical profiles of turbulence intensity (three spires with 72 pieces of roughness elements, X=0, Y=0)
Figure 5.26 Vertical profile of streamwise wind speed fitting curve (three spires with 72 pieces of roughness elements, X=0, Y=0)

Figure 5.27 Horizontal profile of streamwise wind speed (three spires with 72 pieces of roughness elements, X=0, Z=-400 mm)
Figure 5.28 Horizontal turbulence intensity (three spires with 72 pieces of roughness elements, X=0, Z=-400 mm)
5.4.2 Three spires with 144 pieces of roughness elements (4% frontal area density)

The vertical profiles of streamwise wind speed and turbulence intensity at X=0 in the testing plane of Y=0 are shown in Figure 5.29 and 5.30 respectively. As can be seen from the figures, when three spires are combined with 144 roughness elements, the wind speed in the freestream is about 11.89 m/s and the thickness of the boundary layer is 1000 mm of which a turning point appears in the turbulence intensity profile at Z=100 mm. The turbulence intensity in the freestream is 0.22%. Curve fitting is applied to the vertical dimensionless wind speed profile, which yields an exponent 0.22 for the power law curve, as portrayed in Figure 5.31. The exponent \( \alpha \) is larger than that in the case of frontal area density of 2%. Compared with the results in the empty tunnel, the horizontal profile of streamwise wind speed and the turbulence intensity profile measured at X= 0 in the horizontal plane of Z=-400 mm, which are shown respectively in Figure 5.32 and 5.33, exhibit similar shapes. Within this horizontal plane, the freestream wind speed is 11.22 m/s, and the freestream turbulence intensity is 0.79%. They agree respectively with those in the vertical profiles at the same height.
Figure 5.29 Vertical profile of streamwise wind speed (three spires with 144 pieces of roughness elements, X=0, Y=0)

Figure 5.30 Vertical profile of turbulence intensity (three spires with 144 pieces of roughness elements, X=0, Y=0)
Figure 5.31 Vertical profile of streamwise wind speed fitting curve (three spires with 144 roughness elements, X=0, Y=0)

Figure 5.32 Horizontal profile of streamwise wind speed (three spires with 144 roughness elements, X=0, Z=-400 mm)
Figure 5.33 Horizontal profile of turbulence intensity (three spires with 144 roughness elements, X=0, Z=-400 mm)
5.4.3 Three spires with 200 pieces of roughness elements (frontal area density of 5.56%)

Figures 5.34 and 5.35 show respectively the vertical profiles of the mean wind speed and the turbulence intensity at X=0 in the vertical testing plane of Y=0 when the fan motor frequency is at 48 Hz. Results show that the thickness of the generated boundary layer is 1000 mm. Within the boundary layer, the shape of the vertical profile of streamwise wind speed is close to a power function curve with an exponent of approximately 0.1851, as shown in Figure 5.36. In the freestream, the wind speed varies slightly between 12 m/s and 12.1 m/s with a turbulence intensity of 0.21%. The horizontal profile of streamwise wind speed measured at X=0 and Z= -400 mm is shown in Figure 5.37 and the Horizontal profiles of turbulence intensity at the same location in Figure 5.38. Both of them manifest similar shapes as those in the empty wind tunnel. The wind speed is 11.19 m/s in the free stream at X=0 in the horizontal testing plane of Z=-400 mm. It nearly equals to wind speed of 11.25 m/s at the same height of the vertical profile of streamwise wind speed in Figure 5.34. From Figure 5.38, the freestream turbulence intensity is 0.77%, which is very close to 0.8% observed from the Vertical profiles of turbulence intensity in Figure 5.35.

Figure 5.39 gives the power spectrum of the wind speed measured at the center of the test section, i.e. X=Y=Z=0. According to Roach (Roach, 1989), the integral length scale at this measurement point can be computed from

\[ \Lambda_X = \left[ \frac{E(f)U_{mean}}{4\bar{u}^2} \right]_{f \to 0} \]  \hspace{1cm} (5.9)

where \( E(f) \) is the energy contained in eddies with respect to frequency, \( U_{mean} \) is the mean wind velocity, \( \bar{u} \) is the standard deviation of the wind velocity. Thus the length scale is
calculated to be 78.28 mm at 910 mm above the wind tunnel floor. In Figure 5.39, there are three ranges: energy containing range, inertial sub-range, and dissipation range. The slope of the power spectrum curve in the inertial sub-range can be estimated as follows: Choose two points from the power spectrum curve, for example points \((60, 10^{-3})\) and \((236, 10^{-4})\). The slope of the line connecting these two points is -1.685, which is close to the theoretical value of \(-1.667\) \((-5/3)\) for the inertial sub-range. This verifies that the process of signal treatment is correct. The distribution of integral length scale along vertical direction at \(X=0, Y=0\), is shown in Figure 5.40. The integral length scale at the bottom close to the wind floor is 1.11 mm. Within the boundary layer, it is 57.38 mm, whereas in the freestream, it is 90.84 mm.

Figure 5.34 Vertical profile of streamwise wind speed (three spires with 200 pieces of roughness elements, \(X=0, Y=0\))
Figure 5.35 Vertical profiles of turbulence intensity (three spires with 200 pieces of roughness elements, X=0, Y=0)

Figure 5.36 Vertical profile of streamwise wind speed fitting curve (three spires with 200 pieces of roughness elements, X=0, Y=0)
Figure 5.37 Horizontal profile of streamwise wind speed (three spires with 200 pieces of roughness elements, X=0, Z=-400 mm)

Figure 5.38 Horizontal profiles of turbulence intensity (three spires with 200 pieces of roughness elements, X=0, Z=-400 mm)
Figure 5.39 Power spectrum at point (0, 0, 0)

Figure 5.40 Integral length scale on vertical middle plane (X= 0 mm, Y= 0 mm)
5.5 Summary

In the Irwin’s method, it was proposed that the thickness of the generated boundary layer would be governed by the height of the spires. This has been verified through the experiment results of the spire-only case. The testing results show that the spires play an important role in disturbing the flow, which determines the boundary layer thickness. From the location close to the wind tunnel floor to the free stream, the shape of the Vertical profiles of turbulence intensity varies corresponding to the shape of a spire.

The roughness elements cover a large zone downstream of the spires and provide correction effects to the shape of the vertical profile of streamwise wind speed and the associated power law exponent $\alpha$. Comparison with the empty tunnel results show that the wind speed profile in the testing section downstream of the array of roughness elements is affected till roughly 6.5 times of the roughness element height. It is found that, when only roughness elements are presented, the turbulence intensity within the boundary layer increases linearly with height, which is different from that of the empty tunnel case. These suggest that the effect of roughness elements is to retard the wind speed at the bottom of the vertical profile of streamwise wind speed.

The spires and roughness elements combined technology was proposed by Irwin (1979). Three cases were tested: three spires with 72 pieces of roughness elements, three spires with 144 pieces of roughness elements, and three spires with 200 pieces of roughness elements. The three spires generated a flow field with a power law velocity profile and the roughness elements increased the exponent of the power law velocity profile at the same time. All of the vertical profiles of streamwise wind speed and turbulence intensity of these
three cases are measured. In the case of three spires with 200 roughness elements, the turbulence length scale along the vertical direction at X=0, Y=0 and the power spectrum of the wind speed data sampled at X=0, Y=0 and Z=0 are analyzed. In the power spectrum results, the slope in the inertial sub-layer range equals to the theoretical value of \(-5/3\).

To illustrate the impact of different types of passive device arrangement on the flow characteristics in a wind tunnel, the vertical profiles of streamwise wind speed measured at X=0 in the plane of Y=0 for the cases of empty tunnel, 3 spires only, 200 roughness elements only, and the combination of three spires with 200 roughness elements are portrayed together in Figure 5.41, it is clear that the spires would generate a power law wind speed profile and the roughness elements would retard the velocity of the bottom of the wind speed profile.

![Figure 5.41 Vertical profiles of streamwise wind speed under different types of passive device arrangement (X=0, Y=0)](image-url)
The Vertical profiles of turbulence intensities for the same four cases in Figure 5.41 are presented in Figure 5.42. Results show that the presence of spires in the tunnel considerably increases the turbulence intensity in the boundary layer. Roughness elements increase turbulence intensity in the boundary layer, too.

![Graph of Vertical profiles of turbulence intensity under different types of passive device arrangement (X=0, Y=0)](image)

Figure 5.42 Vertical profiles of turbulence intensity under different types of passive device arrangement (X=0, Y=0)

Figure 5.43 depicts the comparison between the dimensionless wind speed profile and the theoretical power law wind speed profile with an exponent of 0.33. A very important phenomenon can be observed from Figure 5.44. The power law exponent \( \alpha \) of the wind speed profile varies monotonically with respect to the frontal area density of the roughness element. If imagine the tunnel floor is fully covered by roughness elements, i.e. the frontal area density is 100%, it is equivalent to the case of an empty wind tunnel with a
lifted ground plane. Thus, the $\alpha$-value for this extreme case would be almost identical to the original empty tunnel, which is 0.1357. This implies that the power law velocity exponent $\alpha$ would increase by adding certain amount of roughness elements into the empty tunnel till the number of roughness element achieved a “saturate” frontal area density which yields the maximum $\alpha$-value. Afterwards, with further increase of roughness elements, $\alpha$-value would gradually decrease until reaches the magnitude corresponding to the frontal area density of 100%. Figure 5.45 portrays this hypothesis pattern between the $\alpha$-value and the frontal area density of roughness elements. Although due to restriction of time frame, only three frontal area density cases were tested in the current study, the curve shown in Figure 5.44 clearly belongs to the ascending branch of the hypothetic curve illustrated in Figure 5.45. More cases need to be tested to verify the hypothetic curve in Figure 5.45.

Figure 5.43 Comparison between power law wind speed profile with exponent 0.33 and the dimensionless vertical profiles of streamwise wind speed under different frontal area density of the roughness elements
Figure 5.44 Relation between frontal area density of roughness elements and exponent $\alpha$ of power law wind speed profile

Figure 5.45 Hypothetic curve between $\alpha$-value and frontal area density
CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In the current study, the spire-roughness-element technology has been applied to simulate atmospheric boundary layer in a new wind tunnel facility at the University of Windsor. After setting up all the instrumentations and developing data acquisition and analysis software in the Labview® environment, the flow quality at the test section of the empty wind tunnel is evaluated first. The relation between the fan motor frequency and the generated wind speed is determined. The symmetry and the uniformity of the flow field, as well as the freestream turbulence intensity have been checked, too. The noise sources which cause distortion of the raw data have been identified and data treatment has been implemented in the software for data analysis. Subsequently, two types of passive devices, i.e. spires and roughness elements, have been designed and manufactured. The flow properties at the test section with the presence of spires alone, roughness elements alone, and spires combined with roughness elements have been measured.

The main findings of the current study are given as follows:

1. The relation between the fan motor frequency and the generated wind speed has been determined. The wind speed in the wind tunnel varies linearly with the frequency of the fan motor and equals to 0.25 times of it. The maximum achievable wind speed in the CFI wind tunnel is 15 m/s.
2. The uniformity and symmetry of the flow field in the tunnel have been evaluated. The results show that the flow field in the CFI wind tunnel is uniform and symmetrical.

3. The noise sources have been identified and eliminated, which include the signal interference between cables and the static pressure fluctuation. After eliminating those noises, the turbulence intensity in the freestream of the empty wind tunnel is 0.17%.

4. The thickness of the boundary layer at the testing section generated by installing 3 spires at the inlet of the test section is measured to be 1 m, which agrees with the boundary layer thickness predicted by the Irwin’s approach.

5. Roughness elements increase the thickness of the boundary layer and retard the wind speed at the bottom of a profile. It is roughly 6.5 times the height of the roughness elements.

6. When spires are combined with roughness elements, the generated boundary layer thickness will be governed by spire size, whereas roughness elements would change the exponent of the power law velocity profile. A proper combination of spires and roughness elements would not only generate the desired boundary layer thickness, but also produce an associated corresponding to a certain terrain condition vertical profile of streamwise wind speed with the targeted \( \alpha \)-value.

7. A certain relation exists between the frontal area density of roughness elements and the exponent \( \alpha \) of the vertical profile of streamwise wind speed. For the cases tested in the current study, results show that by increasing roughness element frontal area density from 0 to 5.56%, the \( \alpha \)-value increases from 0.1357 to 0.23497.
6.2 Recommendations

To better understand how different design and arrangements of various types of passive devices and their combinations would affect simulation of atmospheric boundary layer in a wind tunnel, more experimental studies need to be carried out in the CFI wind tunnel.

1. The generated boundary layer thickness in the test section:

To verify the predicted boundary layer thickness according to Irwin’s approach, several sets of spires with different size and number need to be designed and manufactured. Their respective impact on the resulted vertical profile of streamwise wind speed at the test section need to be evaluated.

2. The relation between the exponent of the power law wind speed profile and the frontal area density of roughness elements.

More tests need to be conducted for the spires combined with roughness elements case by further increasing the frontal area density of roughness elements. This will allow to obtain a better understanding of the relation between the exponent of the power law wind speed profile and the frontal area density of roughness elements, which can be used as a guidance to design passive devices and their arrangements to reproduce atmospheric boundary layer in the wind tunnel that satisfy requirements of both boundary layer thickness and wind speed profile associated with certain terrain type.
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APPENDIX A: SUMMARY OF VELOCITY SAMPLE UNCERTAINTY CALCULATION

The relative expanded uncertainties on a single velocity sample obtained with a single-sensor hot-wire probe in air, can be summarized in the following tale:

Input data are: \( T_w - T_0 = 200 \, ^\circ C, U = 15 \, m/s, A = 1.396, B = 0.895, \partial U / \partial E = 46.5 \, m/s/volt \)

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Input variants</th>
<th>Typical value</th>
<th>Relative output variants</th>
<th>Typical value</th>
<th>Coverage factor</th>
<th>Relative standard uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta x_i )</td>
<td>( \Delta x_i )</td>
<td>( \frac{1}{U} \Delta y_i )</td>
<td>( \frac{1}{U} \Delta y_i )</td>
<td>( \frac{1}{k} \Delta y_i )</td>
<td>( \frac{1}{k} \Delta y_i )</td>
<td></td>
</tr>
<tr>
<td>Calibrator</td>
<td>( \Delta U_{cal} )</td>
<td>1%</td>
<td>2STDV(100 \cdot \Delta U_{cal})</td>
<td>0.02</td>
<td>2</td>
<td>0.01</td>
</tr>
<tr>
<td>Linearisation</td>
<td>( \Delta U_{fit} )</td>
<td>0.5%</td>
<td>2STDV(100 \cdot \Delta U_{fit})</td>
<td>0.01</td>
<td>2</td>
<td>0.005</td>
</tr>
<tr>
<td>A/D resolution</td>
<td>( E_{AD} / n )</td>
<td>10 v, 12 bit</td>
<td>( \frac{1}{E_{AD}} \cdot \frac{\partial U}{\partial E} )</td>
<td>0.0008</td>
<td>( \sqrt{3} )</td>
<td>0.0013</td>
</tr>
<tr>
<td>Probe positioning</td>
<td>( \theta )</td>
<td>1°</td>
<td>( 1 - \cos \theta )</td>
<td>0.00015</td>
<td>( \sqrt{3} )</td>
<td>( \approx 0 )</td>
</tr>
<tr>
<td>Temperature variations 1</td>
<td>( \Delta T )</td>
<td>1°C</td>
<td>( \frac{1}{U} \cdot \frac{\Delta T}{(T_w - T_0) \cdot B \cdot U^{-0.5} + 1} )</td>
<td>0.013</td>
<td>( \sqrt{3} )</td>
<td>0.008</td>
</tr>
<tr>
<td>Temperature variations 2</td>
<td>( \Delta T )</td>
<td>1°C</td>
<td>( \frac{\Delta T}{273} )</td>
<td>0.004</td>
<td>( \sqrt{3} )</td>
<td>0.002</td>
</tr>
<tr>
<td>Ambient pressure</td>
<td>( \Delta P )</td>
<td>10 kPa</td>
<td>( \frac{P_0}{P_0 + \Delta P} )</td>
<td>0.01</td>
<td>( \sqrt{3} )</td>
<td>0.006</td>
</tr>
<tr>
<td>Humidity</td>
<td>( \Delta P_{wv} )</td>
<td>1 kPa</td>
<td>( \frac{1}{U} \cdot \frac{\partial U}{\partial P_{wv}} \cdot \Delta P_{wv} )</td>
<td>0.0006</td>
<td>( \sqrt{3} )</td>
<td>( \approx 0 )</td>
</tr>
</tbody>
</table>

Relative expanded uncertainty: \( U(U_{sample}) = 2 \sum \left( \frac{1}{k \cdot U} \Delta y_i \right)^2 = 0.03 = 3\% \)

Refer to: E. J. Finn, How to measure turbulence with hot-wire anemometers, 2002
APPENDIX B: LABVIEW® PROGRAMS

1 Main program initialization
2 Dynamically call a sub-VI: open a new testing program
3 Dynamically call a sub-VI: load an archive testing file
4 Quit to Window
5 Sampling program initialization
6 DAQ sampling program
7 Sampling program exit
8 Load a TDMS file
9 Data analysis program
10 Load program exit
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