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Simulation of Atmospheric Boundary Layer in an Open-Loop Wind Tunnel Using Spire-Roughness-Element Technique

PENGZHAO SONG
University of Windsor

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Simulation of Atmospheric Boundary Layer in an Open-Loop Wind Tunnel Using Spire-Roughness-Element Technique

By

Pengzhao Song

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

Windsor, Ontario, Canada

2017

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Simulation of Atmospheric Boundary Layer in an Open-Loop Wind Tunnel Using Spire-Roughness-Element Technique

By

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ABSTRACT

Wind tunnel is an important tool for wind-related researches, such as studying the wind-induced response of man-made structures, which are submerged in the ABL. Different terrain conditions would have the different influence on the studied object, so a proper simulation for the ABL using passive simulation devices, spire and roughness element, is essential. The objectives of this study include the design and the manufacture of the spires and roughness elements, studying the effect of the spire and roughness element on the simulated flow characteristics of the generated the ABL. And the atmospheric boundary layers of terrain type “A” and “B” have been simulated in an open-loop wind tunnel using spires combined with roughness.

Key words: ABL simulation, Spire-roughness-element technique and wind tunnel tests.
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I would like to show my deepest gratitude to my parents, Mulin Song and Hengmei Zhao, for giving me a chance to study at the University of Windsor, supporting my life and encouraging me every day. I’d like to show my appreciate to my dearest uncle and aunt, Xilin Song and Jianjun Qi, for taking care of my father’s health and supporting my study and life in these three years.
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### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$A_f$</td>
<td>frontal area of the roughness element</td>
</tr>
<tr>
<td>$A_s$</td>
<td>total frontal area of all the spires</td>
</tr>
<tr>
<td>$b_s$</td>
<td>base width of the spire</td>
</tr>
<tr>
<td>$C_n$</td>
<td>hot-wire calibration coefficient</td>
</tr>
<tr>
<td>$C_D$</td>
<td>drag coefficients</td>
</tr>
<tr>
<td>$C_f$</td>
<td>effective surface friction coefficient</td>
</tr>
<tr>
<td>$d$</td>
<td>width of test section</td>
</tr>
<tr>
<td>$E$</td>
<td>voltage</td>
</tr>
<tr>
<td>$f_L$</td>
<td>non-dimensional frequency</td>
</tr>
<tr>
<td>$f_m$</td>
<td>motor frequency</td>
</tr>
<tr>
<td>$H$</td>
<td>height of the test section</td>
</tr>
<tr>
<td>$h_s$</td>
<td>height of the spire</td>
</tr>
<tr>
<td>$l_u$</td>
<td>turbulence intensity</td>
</tr>
<tr>
<td>$K$</td>
<td>surface drag coefficient</td>
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<tr>
<td>$k$</td>
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<tr>
<td>$\bar{L}_x$</td>
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<tr>
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<td>$L_u$</td>
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<tr>
<td>$N_s$</td>
<td>number of spires</td>
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</tr>
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<td>$U$</td>
<td>wind velocity</td>
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**Greek Symbols**

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<td>$\alpha$</td>
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<tr>
<td>$\sigma$</td>
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</tr>
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<td>$\theta$</td>
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</tr>
<tr>
<td>$\delta$</td>
<td>boundary layer thickness</td>
</tr>
<tr>
<td>$\rho$</td>
<td>correlation function</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>autocorrelation factor</td>
</tr>
<tr>
<td>$\tau$</td>
<td>time</td>
</tr>
<tr>
<td>$\tau_A$</td>
<td>integral time scale</td>
</tr>
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**Latin and other Symbols**

<table>
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<tr>
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<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta(*)$</td>
<td>relative uncertainty of (*)</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>time interval between consecutive samples</td>
</tr>
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CHAPTER 1 INTRODUCTION

1.1 Background

Wind tunnel is an important tool for research in the field of wind engineering. The very first wind tunnel, which was invented and designed by Wenham and Browning in 1871, was dedicated to aeronautic research (ASGB, 1872). In 1930s, researchers at the National Physical Laboratory (NPL) in UK began to study the structural response under wind load in the wind tunnel (Li, 2008). The aeronautic wind tunnels are typically lack of sufficient turbulence and boundary layer thickness and thus incapable of simulating atmospheric boundary layer (ABL) (Burton, 2001). Bailey and Vincent (1943) recognized the importance of ABL flow in studying wind-related structural response and tried to simulate the ABL with a lot of obstacles in a very long tunnel at NPL. This marked the turning point in wind tunnel test history for the purpose of civil engineering (Calderini and Pagnini, 2015). Jensen tested the response of a small shed under wind load in different terrain conditions to identify the importance of faithful reproduction of terrain condition on the validity of the wind tunnel testing results and proposed the “Model Law” in 1958 (Pobertson and Naka, 1980; Davenport, 1992). The model law makes it possible to conduct scaled model test in the wind tunnel, which forms the theoretical foundation of the boundary layer wind tunnel test (Holmes, 2001). In 1958, Cermak designed the first closed-loop boundary layer wind tunnel laboratory in USA (Cermak, 1958). In 1965, Davenport founded the first open-loop boundary layer wind tunnel in the world to study
the effects of wind, water and environmental loads on tall buildings, bridges and other man-made structures (Pires et al, 2013).

When studying wind-induced structural response, since all man-made structures submerge in the ABL, so the ABL plays an important role in wind-related structural research. Along with the development of wind tunnel testing techniques, the application of wind tunnel has been extended to many fields, such as architecture, environment and mechanics (Li, 2008). In addition, various other types of wind tunnel, such as the automotive wind tunnel, the meteorological wind tunnel and the environmental wind tunnel, have been built to satisfy the specific needs of certain type of research and study, such as the wind-induced vibration of man-made structures, the hurricane forecast, the aerodynamic feature of vehicles and the wind-related environmental issues.

Although the application of Computational Fluid Dynamics (CFD) in wind engineering becomes more popular in the last two decades, CFD cannot simulate complex wind flow field because of the limitation of the computer storage capacity (Murakami et al, 1999; Bauer, 2009). Further, the CFD techniques rely on various assumptions, which makes the results usually associated with high uncertainties (Gartmann et al., 2011). The outcomes of the CFD simulation need to be validated by the wind tunnel testing results and/or field measurements. Therefore, the role of wind tunnel test cannot be replaced by CFD simulations. On the other hand, although full-scale measurement can directly provide any information of interest, the cost associated with it is much higher than that of the wind
tunnel test, and to repeat the measurement under the exact same condition would be hardly possible. Therefore, it can be seen from the above that wind tunnel test is still an essential tool in aerodynamic-related research.

Figure 1.1 Open-loop boundary layer wind tunnel at the University of Windsor

The open-loop low-speed boundary layer wind tunnel at the University of Windsor, shown in Figure 1.1, is funded by the Canada Foundation for Innovation (CFI). It was designed for conducting researches related to wind-related civil and environmental issues, such as the wind-induced load on and response of structures and air pollution.
Figure 1.2 Schematic of open-loop boundary layer wind tunnel at the University of Windsor (unit: m)

Figure 1.2 shows the schematic of the open-loop boundary layer wind tunnel at the University of Windsor. The total length of the wind tunnel is 17.6 meters. It consists of the inlet contraction, the honeycomb section, the plain section, the door section, the test section, the transition part, the fan section and the diffuser. The inlet contraction increases the mean velocity of the flow and reduces the pressure loss. The length of the flow development region is about 7.2 m. This region consists of the honeycomb section, the plain section and the door section. The honeycomb screen is installed at the end of the inlet contraction and the thickness of it is 12 mm. The honeycomb cell has a hexagonal shape. It is used to straighten the flow and reduce the level of turbulence. The floor of both plain and door section can be used to set up passive simulation devices for generating ABL. A turn table with a diameter of 1.5m locates at the test section. It can be rotated by 360 degrees. By placing the model on the turn table and rotate it, it can simulate the model loaded by the wind from different directions. The test section has a
cross-sectional dimension of 1.82 m (H) by 1.82 m (W). The transition section is to change the cross-section of the wind tunnel from rectangular to circular shape in order to connect the test section with the diffuser, which is used for decreasing the mean velocity of the flow.

The maximum wind speed of the wind tunnel is up to 16 m/s, which is generated by a 7-blade axial-flow fan with a diameter of 1.7m. The fan is connected to a 60 horsepower AC motor and located between the transition part and the diffuser.

1.2 Motivations

The open-loop boundary layer wind tunnel at the University of Windsor is designed for wind-related researches such as studying the wind-induced response of man-made structures under certain terrain condition. This type of research typically focuses on objects located within the ABL. Different terrain conditions would have different impact on the approaching wind and thus the wind-induced response of the studied object. Therefore, a proper simulation of the ABL above the associated type of terrain is essential for this kind of wind tunnel study.

There are two different types of approach to simulate ABL in the wind tunnel, the active simulation approach (eg. Garratt, 1993; Cheung et al, 2001) and the passive simulation approach (eg. Owen and Zienkiewicz, 1957; Counihan, 1969; Irwin, 1979, 1981; Wittwer and Moller, 2000; Balendra, 2002; Cook, 2003). The details of these two
approaches will be described in the next chapter. In this study, the passive simulation approach will be used. The devices used in the passive simulation approach include grid, spire, wall and roughness element (Owen and Zienkiewicz, 1957; Philips et al, 1999; Hobson-Dupont, 2015). Among these devices, the combination of spires and roughness elements is the most popular. The design of spires can follow Irwin’s approach (Irwin, 1979) and the roughness elements usually have simple geometric shape such as cubic. By properly design and arrange these passive devices in the upstream of the test section, the characteristics of a specific type of ground surface can be simulated. In order to produce the desired ABL flow characteristics, the effect of different kinds of passive devices and their combinations on the simulated ABL flow characteristics needs to be studied. Four types of terrain conditions, i.e. types A, B, C, D, are defined based on their respective ground surface roughness (ASCE, 7-16). Type ‘A’ stands for regular large obstacle coverage, type ‘B’ represents numerous obstacles, type ‘C’ symbolizes no obstacles and type ‘D’ stands for flat terrain condition such as open sea. The target simulating terrain condition of the current study is type “A”, which represents regular large obstacle coverage, such as city center.

The flow characteristics associated with a specific type of terrain condition can typically be described by the mean wind speed profile, the turbulence intensity, the integral length scale and the power spectrum. Therefore, to successfully simulate the ABL associated with a certain terrain type in the wind tunnel, it is essential to reproduce these
associated flow properties. It is learnt from the existing studies (Farell and Iyengar, 1999; Shi et al, 2007) that by using passive devices, the upper part of turbulence intensity of the simulated ABL is typically less than the value of full-scale measurement data, and it is usually difficult to simulate the target integral length scale and power spectrum in the wind tunnel using passive devices. Therefore, in the current study, effort will be made to ensure the proper simulation of the mean wind speed profile associated with terrain type “A”, whereas match the requirement of the turbulence intensity profile, integral length scale profile and the power spectrum will be set relatively loose.

1.3 Objectives

The objectives of this study are proposed as follows:

1. Use the passive approach to simulate the flow properties of the ABL associated with terrain types “A” and “B” in the open-loop wind tunnel at the University of Windsor.

2. Design and manufacture the passive devices used for simulating the ABL in the wind tunnel.

3. Verify Irwin’s approach for spire design by comparing the predicted ABL thickness with that generated in the wind tunnel.

4. Conduct parametric study to investigate the arrangement and configuration of spires and roughness elements on the flow characteristics of the generated boundary layer.
CHAPTER 2 LITERATURE REVIEW

Wind tunnel is widely used for studying the response of aircrafts, vehicles and man-made structures under wind load. In recent years, the application of wind tunnel has been extended to wind-related researches in agriculture, forestry and sports (Li, 2008). Since these issues occur within hundreds of meters beyond the ground surface of earth, i.e. the bottom of the ABL, it is necessary to simulate the corresponding ABL accurately in the wind tunnel prior to experimentally investigating these issues. The wind tunnel designed to simulate ABL is called the atmospheric boundary layer wind tunnel (ABLWT).

A review on the flow properties used to describe ABL will be provided in this chapter, followed by the available approaches for simulating ABL in the wind tunnel.

2.1 Atmospheric boundary layer

The atmospheric boundary layer is the layer of air generated by the friction between the air flow and the surface of the earth above the ground, which is also called the planetary boundary layer (Garratt, 1992). Within this layer, the effects of the surface friction are felt directly (Garratt, 1992; Cermak et al, 1998; Burton, 2001; Mayhew, 2009). As the height above the ground increases, the impact of friction on retarding the movement of air flow decreases and the velocity of the air flow gradually recovers to the gradient wind at the ceiling of the ABL. The range of the ABL thickness over different terrain condition varies greatly, typically from around 450 m for large cities, to 360 m for
suburbs, 270 m for open terrain and 210 m for open sea. (Chen and Wai-Fah, 1997).

As shown in Figure 2.1, the entire ABL can be divided into the inner layer and the outer layer (Garratt, 1992). The inner layer is also called the atmospheric surface layer, which locates at the bottom of the ABL, just above the ground. It typically has a thickness 10% - 20% of that of the ABL (Garratt, 1992; Kaimal et al., 1994). It can be further divided into the interfacial sublayer and the inertial sublayer. The region located at the very bottom of the ABL is the interfacial (roughness) layer and the thickness of it is called the ‘zero-plane displacement’. The inertial sublayer is the region between the interfacial sublayer and the outer layer. It is affected by the ground surface characteristics directly. The outer layer is the portion above the atmospheric surface layer. It is also called the Ekman layer. In this layer, the surface roughness would not affect the flow properties greatly. The part above the ABL is the free atmosphere.
Flow properties within ABL are mainly described by the mean wind velocity profile, the turbulence intensity, the integral length scale and the power spectrum (Simiu and Scanlan, 1996). To simulate ABL in the wind tunnel, the flow characteristics over certain terrain type need to be faithfully reproduced in wind tunnel. However, existing studies (Armitt and Counihan, 1967; Xu, 2007; Pang and Lin, 2008; Avelar et al, 2012) show that by using the passive approach to simulate ABL, the turbulence intensity in the upper part of the simulated ABL is usually not large enough and the integral length scale and the power spectrum are hard to control due to lack of external mechanical energy supply.

Therefore, when simulating the ABL in the open-loop wind tunnel in the current study, reproducing the mean wind velocity profile will be the essential requirement, whereas great effort will be made to satisfy the simulation requirement of the other three flow properties as much as possible.

In the next part, a detailed description of these four main flow characteristics will be provided.

**Mean wind velocity profile**

The vertical profile of the mean wind velocity shows the variation of mean streamwise wind speed along the height, which is a very important parameter for evaluating the quality of the simulated ABL.

The logarithmic wind velocity profile and the power-law wind velocity profile are commonly used in engineering practice to describe the variation of the mean wind speed
along the height.

**Logarithmic wind velocity profile**

The logarithmic wind velocity profile, which was developed by Sutton (1949), is given by Eq. (2.1) and shown in Figure 2.2.

\[
\bar{u}(z) = \frac{u_*}{\kappa} \ln \frac{z - d}{z_0}
\]  

(2.1)

where \( u_* = \sqrt{\frac{\tau_0}{\rho}} \) is the friction velocity; \( \kappa \approx 0.4 \) is the Von Kármán constant based on the wind tunnel tests; \( d \) is the zero-plane displacement; and \( z_0 \) is the surface roughness length, which is the height above the ground where the mean wind speed becomes zero due to the surface roughness effect. For example, in the presence of a forest, the terrain is fully dense. Therefore, the zero-plane displacement \( d \) needs to be considered to modify the mean wind velocity profile because the flow will be raised such that the top of trees would form a new ‘surface of the ground’ (shown in Figure 2.2) (Dyrbye and Hansen, 1997). Since the local air flow is not uniform, the \( z_0 \) value determined by different tests could differ greatly. Table 2.1 lists the relation between the typical terrain conditions and the corresponding roughness length (ASCE, 7-16).
Figure 2.2 Logarithmic wind velocity profile

Table 2.1 Terrain Classification

<table>
<thead>
<tr>
<th>Terrain Description</th>
<th>Roughness Length $z_0$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open sea, fetch at least 5 km</td>
<td>0.0002</td>
</tr>
<tr>
<td>Mud flats, snow; no vegetation, no obstacles</td>
<td>0.005</td>
</tr>
<tr>
<td>Open flat terrain; grass, few isolated obstacles</td>
<td>0.03</td>
</tr>
<tr>
<td>Low crops; occasional large obstacles</td>
<td>0.1</td>
</tr>
<tr>
<td>High crops; scattered obstacle</td>
<td>0.25</td>
</tr>
<tr>
<td>parkland, bushes; numerous obstacles</td>
<td>0.5</td>
</tr>
<tr>
<td>Regular large obstacle coverage</td>
<td>1.0</td>
</tr>
<tr>
<td>City center with high- and low-rise buildings</td>
<td>$\geq 2$</td>
</tr>
</tbody>
</table>
A simple approach to estimate the approximate value of the surface roughness length $z_0$ was proposed by Fang and Sill (1991), which can be expressed as

$$\frac{z_0}{H} = c$$

where $H$ is the mean roughness height and $c$ is a constant with a value of approximately 0.1.

However, when using the combination of spires and roughness elements to simulate ABL in the lab environment, the size, the density and the arrangement of the roughness elements in the wind tunnel could vary, which would greatly affect the generated roughness length. Lettau (1969) indicated that if both the size of and the spacing between the roughness elements are uniform, the roughness length could be predicted based on the frontal area of the roughness elements as

$$\frac{z_0}{H} = 0.5 \frac{A_f}{s}$$

where $A_f = \bar{L}_y \times z_H$ is the frontal area of the roughness element, $\bar{L}_y$ and $z_H$ are the
width and the height of the roughness element, respectively; \( s = \bar{D}_x \times \bar{D}_y \) is the total plan area per roughness element, \( \bar{D}_x \) and \( \bar{D}_y \) are the width and the length of the total plan area per roughness element, as shown in Figure 2.3.

According to the study by Jia et al (1998), the empirical equations, Eqs. (2.2) and (2.3), fit well with the wind tunnel testing results.

A new method to calculate the log-law form of the mean wind velocity profile parameters for the simulated ABL in the wind tunnel was proposed by Liu et al (2003). This method used the turbulence intensity profile measured by a one-dimensional hot-wire anemometer to calculate the surface roughness length \( z_0 \) based on the empirical expression given by ESDU 74030 and ESDU 74031 (Engineering Science Data Unit). The calculated surface roughness length was then substituted into the logarithmic mean wind speed profile, Eq. (2.1), to find the friction velocity \( u_* \). Results showed that this method could give more consistent and stable \( u_* \) value than applying regression analysis to the wind speed profile.

**Power-law wind velocity profile**

The power-law wind velocity profile is typically used in practice to describe the variation of mean wind speed along the height. It utilizes a power law model and only has one unknown exponent. The formula is shown below (Hellman, 1916):

\[
\frac{\bar{U}(z)}{\bar{U}(Z_{ref})} = \left(\frac{Z}{Z_{ref}}\right)^\alpha
\]  

(2.4)
where $Z_{ref}$ is the reference height, typically taken as 10m above the ground surface; $ar{U}(Z_{ref})$ is the mean wind velocity at the reference height $Z_{ref}$; $\bar{U}(z)$ is the mean wind velocity at height $z$; $\alpha$ is the power exponent, which is related to the ground surface roughness or the terrain condition. ASCE 7-16 defines four different exposure types and describes the associated terrain conditions as listed in Table 2.2.

Irwin (1979) pointed out that estimating mean wind speed using the logarithmic wind speed profile was more accurate and reliable than using the power-law profile in the lowest 10-20 m of the ABL. However, it cannot be used to estimate the height below the zero-plane displacement because the logarithms of negative numbers do not exist and it is not convenient to integrate (Holmes, 2001). Besides, it is not valid at very high altitudes above the ground (Dyrbye and Hansen, 1996) and Eurocode 1 uses it for the mean wind speed profile up to 200 m above the ground (Eurocode, 1993). The power-law profile is an empirical formula, which does not have any theoretical justifications. However, it is commonly used to estimate the average wind speed profile in wind engineering applications because the profile of power-law matches the variation of mean wind speed along the height well enough for the engineering purpose within the ABL thickness and it only has one unknown exponent in the formula. (Holmes, 2001).
Table 2.2 Terrain roughness category and exposure type (ASCE 7-16)

<table>
<thead>
<tr>
<th>Exposure type</th>
<th>Terrain Description</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Open sea, Fetch at least 5 km</td>
<td>0.12</td>
</tr>
<tr>
<td>C</td>
<td>Mud flats, snow; no vegetation, no obstacles</td>
<td>0.16</td>
</tr>
<tr>
<td>B</td>
<td>Parkland, bushes; numerous obstacles</td>
<td>0.22</td>
</tr>
<tr>
<td>A</td>
<td>Regular large obstacle coverage</td>
<td>0.33</td>
</tr>
</tbody>
</table>

**Turbulence intensity**

Turbulence is often considered as the superposition of eddies with different sizes transported by the mean air flow. The simplest descriptor of atmospheric turbulence is the turbulence intensity, which is the measure of the fluctuating wind power (Tamura et al, 2013). It is defined as the ratio between the standard deviation of the velocity fluctuation and the mean velocity, i.e.

\[
I_u = \frac{\sigma_u(z)}{\bar{U}(z)} \tag{2.5}
\]

\[
I_v = \frac{\sigma_v(z)}{\bar{U}(z)} \tag{2.6}
\]

\[
I_w = \frac{\sigma_w(z)}{\bar{U}(z)} \tag{2.7}
\]

where \( \sigma_u^2 = \frac{1}{T} \int_0^T u^2 \, dt \), \( \sigma_v^2 = \frac{1}{T} \int_0^T v^2 \, dt \), \( \sigma_w^2 = \frac{1}{T} \int_0^T w^2 \, dt \); \( u, v \) and \( w \) stands for the fluctuating wind velocity component in the horizontal stream wise, the horizontal lateral and the vertical directions, respectively; \( \bar{U}(z) \) is the mean wind velocity. The empirical formula provided by ESDU 75001(1975) for estimating the turbulence intensity of ABL flow is
\[ I_u = \frac{1}{\ln(z/z_0)} \left[ 0.867 + 0.566 \log z - 0.246 (\log z)^2 \right] \lambda \]  
\[ \lambda = \begin{cases} 
0.76, & z_0 > 0.02m \\
\frac{z_0^{0.07}}{z_0}, & z_0 \leq 0.02m 
\end{cases} \]  

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

After comparing with the codes by the American Society of Civil Engineers (ASCE 7-98), the Standards Austria (AS1170.2-89), the National Building Code of Canada (NBCC, 1995), the Architectural Institute of Japan (AIJ, 1993), and the Eurocode-1993 of Europe, Zhou et al (2002) concluded a general formula to estimate the turbulence intensity of ABL flow, which is

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

where \( c \) and \( d \) are the constants corresponding to the variation of terrain condition. The difference between the above codes lies in the value of these two constants, which are listed in Table 2.3.

Table 2.3 Turbulence intensity constants \( c \) and \( d \) in the codes of different countries (Zhou et al, 2002)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<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></td>
</tr>
</tbody>
</table>

* The definitions of terrain conditions A, B, C and D are not the same in different countries.

One of the most general and widely accepted empirical formula for determining
turbulence intensity was proposed by Walshe (1973). It can be used to judge the quality of the simulated ABL turbulence intensity and has the form of:

\[ I_u(z) = \frac{\sigma_u}{\bar{U}} = 2.58k\frac{10}{z}^{\alpha} \]  

(2.11)

where \( \sigma_u \) is the standard deviation of the fluctuating component of the streamwise wind velocity; \( \bar{U} \) is the mean streamwise wind velocity; \( z \) is the full scale height measured from the ground surface; \( \alpha \) is the power law exponent; and \( K \) is the surface drag coefficient. The value of \( K \) by Walshe (1973) is given in Table 2.4.

<table>
<thead>
<tr>
<th>Terrain Description</th>
<th>Power-law exponent ( \alpha )</th>
<th>Surface drag coefficient ( K )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open terrain with very few obstacles, e.g. open grass or farmland with few trees, hedgerows and other barriers, etc.; prairie, tundra, shores, and the low islands of inland lakes; desert.</td>
<td>0.16</td>
<td>0.005</td>
</tr>
<tr>
<td>Terrain uniformly covered with obstacles 10-15m in height: e.g. residential suburbs; small towns; woodland and scrub. Small fields with bushes, trees and hedges.</td>
<td>0.28</td>
<td>0.015</td>
</tr>
<tr>
<td>Terrain with large and irregular objects; e.g. centers of large cities, very broken country with many wind-breaks of tall trees, etc.</td>
<td>0.4</td>
<td>0.050</td>
</tr>
</tbody>
</table>

**Integral length scale**

Integral length scale is the average size of flow vortex in a certain direction. It is used as a measurement of the eddy size in the wind flow. If the distance between two spatial points is larger than the integral length scale, the turbulence component \( u \) at these two points are not correlated. It is defined as
\[ L_u^x = \int_0^\infty \rho_u(z,r_x) \, dr_x \]  \hspace{1cm} (2.12)

where \( L_u^x \) is the integral length scale of the turbulence component \( u \) measured in the longitudinal direction \( x \); \( \rho_u(z,r_x) = E[u(x,y,z,t) \cdot u(x + r_x,y,z,t)]/\sigma_u^2(z) \) is the cross-correlation function of the turbulence component \( u \) at two points separated longitudinally along the \( x \)-direction by a distance \( r_x \) and measured simultaneously (Tennekes and Lumley, 1972; Kaimal and Finnigan, 1994).

According to the Taylor’s hypothesis of “frozen turbulence”, a statistical description of the temporal variations of turbulence can be obtained based on the characteristics of the spatial wind velocity field and vice versa (Bahraminasab et al, 2008; Chad et al, 2012), i.e.

\[ \rho_u(z,r_x) = \rho_u^T(z,\tau), \text{ for } r_x = U(z) \cdot \tau \]  \hspace{1cm} (2.13)

where \( \rho_u^T(z,\tau) = E[u(x,y,z,t) \cdot u(x,y,z,t + \tau)]/\sigma_u^2(z) \) is the autocorrelation function. It indicates how much information a measurement of the turbulence component \( u(x,y,z,t) \) in the mean wind direction would provide to the value of \( u(x,y,z,t + \tau) \) measured time \( \tau \) later at the same place. Therefore, the integral length scale can be calculated based on the time history of wind speed \( U(z,t) \) measured at height \( z \) above the ground.

The quality of the simulated ABL integral length scale along the height can be evaluated by comparing the results obtained in the wind tunnel test with those predicted by the empirical formulae. The two commonly used empirical formulae for predicting
The integral length scale in ABL are given below.

The empirical formula by Walshe (1973) is

\[ L_u^x = 101 \left( \frac{Z}{10} \right)^\alpha \]  

(2.16)

where \( \alpha \) is the power-law exponent of the mean wind velocity profile, and the predicted \( L_u^x \) has a unit in meter.

The empirical formula proposed by Cook (1978) is

\[ L_u^x = 25(z - z_d)^{0.35}z_0^{-0.063} \]  

(2.17)

where \( z_d \) is the zero-plane displacement and \( z_0 \) is the surface roughness length.

It is worth mentioning that the magnitude of the integral length scale predicted by different empirical formulae varies.

**Power spectrum density**

Power spectrum of a signal describes the distribution of energy contained in it over the frequency domain. Thus, the power spectrum of the wind velocity time history \( U(t) \) shows how the energy contained in the oncoming flow distributed over the frequency domain.

The power spectrum density \( s_u(z, n) \) is obtained by applying Fourier transform to \( \rho_u^T(z, \tau) \), which is the autocorrelation of wind velocity time history \( U(t) \). The non-dimensional power spectrum density \( R_N(z, n) \) is calculated as follows:

\[ R_N(z, n) = \frac{n \cdot s_u(z, n)}{\sigma_u^2(z)} \]  

(2.18)

where \( n \) is the frequency in “Hz”; \( z \) is the height of the observation point; \( s_u(z, n) \) is the
power spectrum of the along-wind turbulence component \( u(z, t) \); and \( \sigma_u(z) \) is the standard deviation of the wind velocity time history \( U(t) \).

Kolmogorov (1941) created a milestone in the history of understanding the structure of turbulence. He pointed out that turbulent energy was generated in large eddies and dissipated in small eddies. This process is known as the turbulent energy cascade.

There are three zones in the atmospheric turbulence power spectrum (Counihan, 1975), i.e. the energy containing range, the inertial sub-range and the dissipation range, as shown in Figure 2.4. The shear and buoyancy produce turbulence in the energy containing range (low frequency). In the intermediate frequency region, which is also called the inertial sub-range, the turbulent energy production is balanced by the turbulent energy dissipation and the eddy size changes from large to small.

Invoking Taylor’s hypothesis of “frozen turbulence”, the non-dimensional power spectrum function \( R_N \) of the turbulence in the inertial sub-range is given by Kolmogorov as (Kolmogorov, 1941)

\[
R_N(z, n) = \alpha \varepsilon^{\frac{2}{3}} k^{\frac{-5}{3}}
\]  

(2.19)

where \( \alpha \) is the Kolmogorov constant; \( \varepsilon \) is the energy cascade rate, which is the rate of energy dissipation per unit volume; and \( k \) is the wavenumber, which is defined by \( 2\pi/wavelength \). Both field and lab experiments and numerical simulations were conducted to determine the Kolmogorov constant, which was found to be \( \alpha \approx 2.0 \) (Grant et al, 1962; Frisch, 1995). The Kolmogorov’s -5/3 Law should be observed in the intermediate range.
of the simulated ABL power spectrum (see Figure 2.4), which is the slope of the PSD trend is around -5/3 in log-log coordinates. The vortices eventually dissipate in the third (high frequency) range due to the effect of viscosity. The turbulent energy spectrum is independent of the specific mechanisms of energy generation and dissipation.

![Figure 2.4 Power spectrum of turbulence](image)

Figure 2.4 Power spectrum of turbulence

Davenport summarized more than 90 records of natural high wind velocity time histories and developed the Davenport spectrum (Davenport, 1961), which is adopted in the National Building Code of Canada (NBCC, 2010) and the GuoBiao-J code in China (GB, 2010). It is expressed as.

\[
\frac{nS_u(n)}{\bar{u}_{10}^2} = 4kf^2/(1 + f^2)^{4/3}
\]

(2.20)

where \( n \) is the frequency; \( f = (nL)/\bar{u}_{10} \) is the dimensionless frequency; \( \bar{u}_{10} \) is the mean wind velocity at the height of 10 m above the ground; \( L \) is the integral length scale of the upper atmosphere air flow, which is usually taken as 1200 m; and \( k \) is the surface
roughness factor. The limitation of the Davenport power spectrum is that it cannot show the variation of the integral length scale along the height.

The non-dimensional Von Kármán power spectrum density function (Von Kármán, 1948), which is used in the Architectural Institute of Japan code (AIJ, 2006), can be written as

\[ R_N(z, n) = \frac{4f_L}{(1 + 70.8f_L^2)^{5/6}} \]  

(2.21)

where the non-dimensional frequency \( f_L \) is given by

\[ f_L = \frac{nL_u^x(z)}{\overline{U}(z)} \]  

(2.22)

where \( n \) is the frequency in “Hz”; \( L_u^x(z) \) is the integral length scale of the turbulence component \( u \) measured in the longitudinal direction \( x \) at the height of \( z \) m above the ground; and \( \overline{U}(z) \) is the mean wind velocity at height of \( z \) m above the ground.

The ASCE 7-16 in US uses the Kaimal spectrum (Kaimal, 1972). It can be described as

\[ R_N(z, n) = \frac{2\lambda f_z}{(1 + \lambda f_z)^{5/3}} \]  

(2.23)

where \( f_z = nz/\overline{U}(z) \) is known as the Monin (or similarity) coordinate, which is essentially the ratio between the height and the wavelength (Monin and Obukhov, 1954). The non-dimensional parameter \( \lambda \) serves to locate the maximum value of the spectrum density obtained for \( f_z = f_{z, max} = \frac{3}{(2\lambda)} \).

The power spectrum density of the simulated ABL can be compared with the above
empirical formulae to evaluate if the energy distribution over the frequency domain is satisfactory or not.

2.2 Approaches of simulating atmospheric boundary layer in wind tunnel

Simulation of ABL in wind tunnel can be achieved by either natural formation or introducing man-made devices.

Typically a boundary layer of 0.5-1.0 m thickness can be developed naturally over a rough floor after a development length of 20 to 30 m. However, natural formation of ABL requires a long flow development section, which limits its application. The wind tunnel at the Western University developed by Prof. Davenport uses this approach to simulate ABL. It has a flow development length of 33 m.

Another approach is to introduce man-made devices, such as spires, fences, uniform grid, roughness elements and the combination of some of them (Owen and Zienkiewicz, 1957; Counihan, 1969; Cook, 2003), to form ABL in the wind tunnel, which is widely adopted in different wind tunnels all around the world.

The ABL simulation approaches can be classified into active simulation approach and passive simulation approach depending on whether it adopts controllable devices or not. The techniques used in these two approaches are reviewed below:

2.2.1 Passive simulation approach

The passive simulation approach utilizes man-made devices, such as spires, roughness
elements, fences, uniform grid and the combination of some of them, to thicken the boundary layer in the wind tunnel (Owen and Zienkiewicz, 1957; Counihan, 1969; Cook, 2003). These devices cannot only block certain cross-sectional area of the wind tunnel, but also generate eddies to reproduce the characteristics of wind flow over certain terrain condition in nature. From the perspective of energy conversion, the passive simulation approach transfers part of the kinetic energy in the oncoming flow to the kinetic energy in turbulent flow and no additional energy is supplied to the wind flow. Besides, since the passive simulation approach uses relatively simple devices, so it is more cost effective.

Owen and Zienkiewicz (1957) adopted a grid formed by parallel rods with varying spacing to obtain a nearly shear flow in a wind tunnel (shown in Figure 2.5). The principle of this grid is to develop a blockage to influence the flow. The varying spacing between the rods produced a linear or logarithmic variation in the mean wind velocity profile at large distance downstream.

Figure 2.5 Arrangement of the grid and coordinate system by Owen and Zienkiewicz (1957)

An array of non-uniformly spaced flat plates (Figure 2.6) was adopted to simulate
ABL in a wind tunnel by Phillips et al (1999). Both the spacing between the two adjacent plates and the length of the flat plate can control the flow characteristics. The weak shear flow with zero vertical pressure gradients can be simulated by this approach.

![Figure 2.6 Schematic of array of differently spaced flat plates in wind tunnel used by Phillips et al (1999)](image)

The combined use of triangular spires and roughness elements are the most commonly used passive simulation technique (shown in Figure 2.7). The spires act as eddy generators and are used to block the air flow in the wind tunnel. Both the shape and the width of the spires can influence the turbulence intensity and the integral length scale in the upper part of the flow field. The area of the spires, which determines the blockage ratio of the wind tunnel cross-section, largely controls the wind speed profile. The gradient of both the mean wind speed profile and the turbulence intensity profile are large at the bottom of the ABL. The roughness elements can be used to modify the simulated flow condition at the bottom part of the ABL to better simulate the surrounding terrain condition (Owen, 1957; Philips et al, 1999; Hobson-Dupont, 2015).
Figure 2.7 Schematic of spires and Roughness elements in a rectangular working-section by Irwin (1981)

Farell and Iyengar (1999) reproduced the ABL over the urban terrain condition in the St. Anthony Falls Laboratory (SAFL) wind tunnel. Quarter-elliptic, constant-wedge-angle spires or triangular flat spires and a castellated barrier wall were applied to meet the requirement of necessary initial momentum defect and a fetch of roughness elements were used to simulate terrain conditions, which was introduced by Counihan (1969). The results of the test showed that if triangular spires were used, the simulated boundary layer thickness would be roughly 80% the height of the spires. Whereas if the quarter-elliptic spires were applied, the generated boundary layer thickness would be similar to the height of the spires. The results of the simulated wind velocity profile agreed well with the power-law model, with a power exponent of 0.28. The simulated turbulence intensity results indicated that this simulation could be used to model the terrain condition near the center of the urban and suburban with numerous closely spaced high buildings at scales
around 1:500.

In the experimental study by Avelar et al (2012), different combinations of spires, barrier and roughness elements were used to simulate ABL. Results showed that the spires played an important role in defining the mean wind velocity profile, the barriers contributed to the momentum near the bottom of the ABL to adjust the shape of the corresponding wind velocity profile. In addition, varying density of the roughness elements could also modify the bottom part of the wind velocity profile.

Balendra et al (2002) performed a series of wind tunnel tests to evaluate flow characteristic in the NUS-HDB wind tunnel to verify its adequacy for natural wind simulation. It was found that in the empty wind tunnel, the thickness of the boundary layer was about 300mm and the maximum velocity deviation at the center of the turn table was about 3%. Those were similar to the results of the UNNE wind tunnel (Adrian and Sergio, 2000). To simulate the ABL effect in urban terrain condition, five quarter-elliptic wedge spires (shown in Figure 2.8), a castellated barrier and many roughness elements were used. According to the mean wind velocity profile at the center of the turn table, the power-law wind velocity profile exponent $\alpha$ was about 0.29, which was within the range of 0.28~0.30 of the expected power exponent for this type of terrain.
Figure 2.8 Castellated barrier wall and quarter-elliptic wedge spires used by Balendra et al (2002) (unit: mm)

Figure 2.9 Types of eddy generators applied in CERL wind tunnel by Counihan (1969)
Counihan (1969) used four different kinds of vortex generators, i.e. the triangular, the cranked triangular, the plane elliptic and the elliptic wedges (Figure 2.9), to simulate ABL in the Central Electricity Research Laboratories (CERL) wind tunnel. The simulated boundary layer thickness was required to be 4 feet. According to his study, the flow properties of the simulated ABL fitted well with that of the rural terrain condition. The required length of flow development section should be 4-5 times of the targeted boundary layer thickness.

Standen (1972) adopted various different shapes of spires to generate thick shear layer. For example, the standard half-width spires with height varying from 6′′ to 7′′, the triangular plates without central section shown in Figure 2.10(a) and with a rear splitter shown in Figure 2.10(b). With his method, the ABL can be well simulated up to 450 m. But the ratio between the boundary layer thickness and the spire height should be refined rather than remain as a constant for all spire sizes.
Irwin (1981) improved Standen’s method and pointed out that the fine details of the spires were not that important. He developed a new approach to design spires, the shape of them was triangular. It was found that by mounting a set of triangular shape spires at the inlet of the wind tunnel and followed by the arrangement of roughness elements downstream, the vertical profile of streamwise mean wind velocity matched well with the full-scale measurement data, and the turbulence structure of the simulated atmospheric boundary layer, such as the turbulence intensity, the integral length scale and the power spectrum density, agreed reasonably well with the full-scale ABL data.

Since the passive approach is effective in both the simulation results and the cost, it is widely used in many wind tunnels to simulate ABL. However, the existing experience
(Armitt and Counihan, 1967; Xu, 2007; Avelar et al, 2012) show that turbulence intensity in the upper part of the simulated ABL is typically less than the full-scale data. Further, due to the lack of low frequency mechanical motion, both the integral length scale and the power spectrum of the simulated ABL are not large enough in the low frequency zone (Pang and Lin, 2008). To overcome these drawbacks, active simulation technique is developed.

2.2.2 Active simulation approach

The active simulation technique adds mechanical energy with appropriate frequencies to the wind flow (Garratt, 1993; Cheung et al, 2001), which can increase the low frequency components of the turbulent flow and thus improve the simulation of the integral length scale and the power spectrum in the low frequency range. The most successful active simulation approaches used either oscillating spires (Pang and Lin, 2008) or multiple fans (Cao et al, 2002). The active flow simulation technique requires advanced control technology, such as the adjustable vibration frequency in the case of oscillating spires and the independently adjustable velocity of each fan in the multiple-fan wind tunnel to fine-tune the wind velocity profile and turbulence structure in the simulated flow field.
Pang and Lin (2008) performed an ABL simulation in the TJ-2 wind tunnel of Tongji University through two controllable vibrating spires (shown in Figure 2.11) and the roughness elements. It divided the traditional triangular spires into two symmetrical wings and then connected them by hinges. The two wings made reciprocating motion downstream through computer control. The motion added energy with certain frequency to the flow field. At the same time, this kind of spires also served as a passive turbulence generator. The motion frequency of the spires was controlled by a stepping motor. Results showed that the low frequency vibration of the controlled spire device helped to increase the low frequency energy in the simulated turbulent flow. However, when compared with the natural ABL, the integral length scale of the simulated ABL in the wind tunnel was still not large enough.
Figure 2.12 Schematic of the 3-D multiple-fan wind tunnel

The wind tunnel that uses the technique of the multiple frequency-controlled fans is called the multiple-fan wind tunnel. This kind of active simulation technique was developed in Japan. The multiple-fan wind tunnel of the Miyazaki University, shown in Figure 2.12, used this technique (Cao et al, 2002). The test section of this wind tunnel had a maximum length of 15.5 m, width of 2.6 m and height of 1.8m. The flow condition was adjusted based on the simulation requirement. A total of 99 frequency-controlled fans, arranged in eleven rows with nine fans in each row, was controlled by a computer to generate wind flow with certain characteristics independently through an AC servo-motor driver. At the same time, a hot-wire anemometer was used to monitor the streamwise velocity and the power spectrum downstream. It could match the target ABL through several times of feedback adjustments. In order to add vertical turbulence to the main flow, oscillating airfoils was installed at the inlet of the test section. Results showed that the simulated wind velocity time history matched extremely well with the target aim even at
the velocity sharp changing point, and the generated turbulence parameters were also similar to the target values.

Compared with the passive simulation technique, the active simulation approach can better simulate the longitudinal turbulent integral length scale. The generated integral length scale can be larger than 1 meter. The multiple-fan wind tunnel can even simulate the vertical distribution of the integral length scale. The low frequency mechanical motion would increase the energy contained in large-scale vortices. The energy spectrums at different height agree with the target wind power spectrum.

It can be seen from the above review that although the active simulation approach can provide better ABL simulation results, the cost is too high to be commonly applied in the wind tunnel. Since the Irwin’s method of spire design performs well not only in the mean wind velocity profile of the simulated ABL, but also shows reasonable results in turbulence intensity profile, integral length scale profile and power spectrum, it will be adopted in the current study to simulate ABL in the open-loop boundary layer wind tunnel at the University of Windsor.
CHAPTER 3 EXPERIMENTAL DETAILS

In this chapter, the instrumentations used in the current experimental study will be described. Then, the approach of designing the passive simulation devices and the analysis of experimental data will be illustrated.

3.1 Instrumentations

The wind speed measurement system in the open-loop wind tunnel at the University of Windsor consists of a Dwyer® 160E-01 Pitot static tube, a Dantec Dynamic® 55P16 hot-wire anemometer, a data acquisition system (DAQ) and a computer, as shown in Figure 3.1. The signals collected by the pitot tube and the hot-wire anemometer are recorded by the data acquisition system and then transferred to the computer. Matlab® codes are developed to analyze these data to determine the flow characteristics.

The schematics of wind speed measurement system is shown in Figure 3.1.

![Figure 3.1 Schematics of the wind speed measurement system](image)
3.1.1 Pitot static tube

The pitot static tube consists of two tubes, the total pressure tube and the static pressure tube, which are connected to the total pressure hole and the static pressure hole, respectively. The total pressure hole is drilled down the axis of the tube and several small static pressure holes are drilled around the circumference of the tube near the point tip (shown in Figure 3.2). The total pressure hole is used to collect the total pressure at the point tip of the tube and the static pressure is collected by the static pressure hole (Saleh, 2002). The relationship between the total pressure and the static pressure can be expressed by the Bernoulli’s equation, as shown in Eq. (3.1) (Batchelor, 1967).

\[ P_{\text{total}} = P_{\text{static}} + P_{\text{dynamic}} \]  

(3.1)

where \( P_{\text{dynamic}} \) is the dynamic pressure of the air, which is the difference between the total pressure and the static pressure. The total pressure tube and the static pressure tube connect respectively to the positive and the negative tubes of the differential pressure manometer. The output of the manometer displayed on the screen is the dynamic pressure, which relates to the flow velocity by

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

(3.2)

where \( \rho \) is the air density and \( U \) is the velocity of the air flow. The maximum accuracy of a Pitot static tube is \( \pm 2\% \) in the laboratory application.
The model type of the pitot static tube used in the open-loop wind tunnel is Dwyer® 160E-01. The outside diameter of the tube is 0.79 cm and the length of the depth indicator arm is 25.7 cm. The pitot static tube is used in wind tunnel tests for two purposes, i.e. to calibrate hot-wire anemometer and to monitor the wind velocity in the wind tunnel and
provide a reference wind speed. The details of the hot-wire anemometer calibration will be described in the next section. The pitot static tube used for measuring the wind tunnel reference wind velocity is mounted 250 mm below the tunnel ceiling along the middle line of the tunnel and upstream of the test section to ensure the reference wind velocity will not be influenced by the presence of the ceiling (shown in Figure 3.3). It is connected to the Dwyer® Differential Pressure manometer (shown in Figure 3.4), the accuracy of which is ±1%. The output of the manometer is the dynamic pressure. It can be displayed on the screen. Besides, the signals are also collected by the DAQ and the reference wind velocity in the wind tunnel is calculated by the code for data analysis.

Figure 3.3 The pitot static tube under the ceiling
3.1.2 Hot-wire anemometer

The hot-wire anemometer, also called the Constant Temperature Anemometry (CTA), is used to measure the velocity of fluids. It has very high response frequency, up to 1 MHz. Thus, it is very sensitive to rapid changes in the current and can capture transients without any time lag. The model type of the hot-wire anemometer that used in the current experimental study is 55P16 hot-wire probe from Dantec Dynamics® company. The hot-wire anemometry consists of two prongs with a wire stretched between them, and the wire is made of a material with temperature dependent resistivity (shown in Figure 3.5). When an electric current passed through the wire, it heats the wire. The transfer of heat
from the wire to the flow increases with increasing flow velocity in the surrounding of the wire. Hence if the flow velocity varies, the temperature of the wire also varies, and so does the resistance and voltage of the circuit. The air flow velocity can thus be obtained accurately based on the variation of the voltage (Perry, 1982).

![Figure 3.5 Schematics of hot-wire anemometry](image)

When measuring flow speed, the output of the CTA is in the form of voltage. In addition, the hot-wire probe is very sensitive to the variation of ambient environment conditions. Therefore, before each flow measurement, a calibration of the hot-wire probe needs to be conducted to establish a relation between its voltage output and the measured wind speed.

Calibration of the CTA is conducted by exposing the hot-wire probe to a set of known velocities \( U \) and then recording the corresponding voltage outputs \( E \) from the
CTA. After obtaining a number of \((E, U)\) pairs, curve fitting is applied to determine the transfer function from \(E\) to \(U\).

There are two approaches to calibrate the hot-wire anemometer, i.e. the power-law curve fitting approach and the polynomial curve fitting approach. King (1914) proposed a relation between the voltage and the velocity under the assumption that the fluid properties and the wire resistance remain constant. It is known as the King’s law and is given in an algebraic form as follows

\[ E^2 = A + BU^n \]  \hspace{1cm} (3.3)

where \(E\) is the output voltage of CTA; \(U\) is the fluid velocity; \(A\), \(B\) and \(n\) are constants. According to the King’s law, two pairs of voltage (from hot-wire anemometer) and velocity (from pitot static tube) are used to determine the linear trend line. It was found that \(n=0.45\) was a good starting value in practice (Bruun, 1995; Jørgensen, 2002). The value of the constants \(A\) and \(B\) can be determined according to this line. Vary \(n\) and repeat the trend line until the curve fitting error is acceptable. The relationship between the voltage and velocity can thus be determined. Since \(n\) is slightly dependent and needs to be tried many times to get accurate results, the polynomial curve fitting approach is introduced for hot-wire anemometer calibration.
The polynomial curve fitting is a common approach to calibrate the probe. It usually adopts several pairs of velocity and voltage values to fit the polynomial transfer function, which has the form as follows:

\[ U = C_0 + \sum_{n=1}^{n} C_n \cdot E^n \]  

(3.4)

where \( C_0 \) to \( C_n \) are the calibration coefficients. Depending on the curve fitting error of the hot-wire calibration, the value of the exponent \( n \) is different. It was found that \( n=4 \) or 5 works well for the hot-wire calibration in the wind tunnel tests and thus it is commonly adopted (Bruun, 1971; Al-Kayiem and Bruun, 1986). The polynomial curve fitting performs well in hot-wire calibration and the error percentage between the measured velocity and the velocity calculated based on the calibration coefficients is usually less than 1%. The calculation of the calibration coefficients in the polynomial curve fitting is processed in Matlab® environment and the code is given in Appendix A.

**3.1.3 Traverse system**

Traverse system is typically used to mount a pressure probe and/or a hot-wire anemometry downstream of a test model. The traverse system that used in the current open-loop wind tunnel is a three-axis BISLIDE® traverse system (MN10-0500-M02-31), which is shown in Figure 3.6. The travel distance of it is 127 cm (50"), the repeatability is 0.00005 cm (0.00002") and the straight line accuracy is 0.0076 cm (0.003").
The traverse system is placed at the desired location in the wind tunnel test section.

In order to mount the hot-wire anemometer on the traverse and reduce the effect of the traverse system on the oncoming flow, a “Z” shaped rod and clamps were designed to hold the hot-wire anemometry.

### 3.1.4 Data acquisition system

The data acquisition system (DAQ) from the National Instruments® collects the sensor data and transfers them to the computer through a USB port. In the computer, a software developed in the LABVIEW® environment records the data in terms of the analog voltage. All collected data are then transferred from the “tdms” format in the
LABVIEW® environment to the “m” format which can be further processed and analyzed by the Matlab® code.

3.2 Design of passive simulation device

Because of the advantages of the passive approach in simulating ABL, in terms of its effectiveness in the simulation results and lower cost, it is widely used in many wind tunnels. Among various passive simulation devices, the combined use of triangular shape spires and roughness elements is the most common choice. The spires serve as the eddy generators and the roughness elements are mainly used to refine the simulated ABL and correct the bottom part of the wind velocity profile.

3.2.1 Design of spires

Figure 3.7 Rectangular working sections as a control volume (after Irwin, 1979)
Based on the literature reviewed in Chapter 2, the method of designing triangular shape spires developed by Irwin (1979) is adopted. According to the Irwin’s model, as shown in Figure 3.7, the spires should be mounted at the inlet of the wind tunnel working section in order to meet the requirement of the flow development length. Based on existing experience (Irwin, 1979), any roughly triangular shaped spires would give an acceptable boundary layer simulation at a distance of about 6-spire height downstream of the spires. In addition, spires are spaced laterally at an interval of approximately half the spire height (Irwin, 1979). The spacing between the adjacent spires should be kept the same to ensure uniform air flow in the wind tunnel, i.e.

\[
\text{Spire lateral spacing} = \frac{d}{N_s} \quad (3.5)
\]

where \( d \) is the width of the wind tunnel test section and \( N_s \) is the number of spires. The height of the spire \( h_s \) should be two times of the spires lateral spacing, i.e.

\[
h_s = \frac{2d}{N_s} \quad (3.6)
\]

Irwin (1979) summarized the relationship between the \( \delta/h_s \) and \( \alpha \) from several wind simulations, as shown in Figure (3.8), where \( \delta \) is the expected thickness of the simulated boundary layer, \( \alpha \) is the exponent of the power law velocity profile of the target terrain type and \( h_s \) is the height of the designed spires.
From the figure, the relationship between the $\delta/h_s$ at $X_0 \approx 6h_s$ and $\alpha$ can be written as (Irwin, 1979)

$$\frac{\delta}{h_s} = 0.72 \left( 1 + \frac{1}{2} \alpha \right) \quad (3.7)$$

As shown in Figure 3.7, stations 1, 2 and 3 are defined to be at the inlet of the wind tunnel, at the spires and downstream of the flow development region, respectively. According to Irwin’s method, the working section between station 1 and station 3 is treated as a control volume and the Principle of Conservation of Momentum is applied to derive the design formulae. It is based on that the excess of momentum flux at station 3 over that at station 1 is the force due to pressure drop minus the sum of the reaction force of the spires and frictional forces of the ceiling, walls and floor on the air, i.e.
where the number subscripts refer to stations; \( \rho \) is the air density; \( p \) is the static pressure; \( H \) and \( d \) are the height and width of the test section, respectively; \( C_f \) is the effective surface friction coefficient and \( C_{D_0} \) is the true drag coefficient including aerodynamic interference from adjacent spires; \( U_e \) is the wind velocity above the boundary layer at station 3; \( A_s \) is the total frontal area of all the spires.

After substituting the power-law wind velocity profile, Eq. (2.4), and Eqs. (3.1) and (3.2) into Eq. (3.9), it can be simplified as

\[
A_s = \frac{\psi H d}{(1 + \psi \theta) C_{D_0}} \quad \text{(3.10)}
\]

where \( \theta \) is the blockage factor and \( C_{D_0} \) is the true drag coefficient including aerodynamic interference from adjacent spires. According to the results of Irwin (1979), \( \theta = 1.7 \) and \( C_{D_0} = 1.45 \) for spires with shapes in the range \( 0.05 < b_s/h_s < 0.2 \); \( d \) is the...
width of the test section; and $\psi$ is the coefficient introduced to calculate the required total frontal area of the spires, which is

$$\psi = \beta \left( \frac{2}{1+2\alpha} + \beta - C_f \frac{X_0}{\delta} \frac{1+\alpha}{\alpha} \right)/(1-\beta)^2$$  \hspace{1cm} (3.11)

where $\beta = \left( \frac{\delta}{H} \right) \cdot \left[ \alpha/(1+\alpha) \right]$ and $H$ is the height of the wind tunnel test section; $X_0$ is the distance downstream of the spires, which equals to about 6 times of the spire height and $C_f$ is the floor friction coefficient, which is given by

$$C_f = 0.136 \left( \frac{\alpha}{1+\alpha} \right)$$  \hspace{1cm} (3.12)

Substitute Eq. (3.12) into Eq. (3.11), leads to,

$$\psi = \beta \left( \frac{2}{1+2\alpha} + \beta - \frac{X_0}{\delta} \cdot \frac{0.136\alpha}{1+\alpha} \right)/(1-\beta)^2$$  \hspace{1cm} (3.13)

Substitute Eq. (3.13) into Eq. (3.10), the total frontal area of the spires can be obtained.

Based on the total frontal area, the height and the number of spires, the base of the spires can be computed, i.e.

$$b_s = \frac{2A_s}{N_s \cdot h_s}$$  \hspace{1cm} (3.14)

In this study, the spires are designed to simulate the target ABL in the wind tunnel corresponding to a particular value of $\alpha$ in the power-law wind velocity profile. The $\alpha$ value of terrain type “A” is in the range of 0.33-0.4; whereas the actual atmospheric boundary layer thickness for terrain type “A” is about 450 m (Chen, 1997; Li, 2008). In
order to simulate the actual atmospheric boundary layer in the wind tunnel, the model scale should be determined first, which is the ratio between the simulated ABL thickness in the wind tunnel and the actual ABL thickness. In the current study, the model scale is taken as 1:500 and the actual ABL thickness is 450 m. Thus, the simulated ABL thickness in wind tunnel should be about 0.9 m.

A set of three triangular spires was designed and made by a previous master student (Bai, 2015). They will be used in the current study to conduct extensive parametric studies to achieve better simulation results for terrain type “A”. In addition, another set of five triangular spires will be designed and made to compare the simulation results with the three-spire case. The details of designing spires are shown in Table 3.1.

The dimensions of the five triangular shape spires are designed and shown in Table 3.2, and those of the three-spire case designed by Bai (2015) are also listed. Based on the design, for the five-spire case, each of them has a height of 0.73 m and a base of 0.11 m. The schematic of the designed spires is shown in Figure 3.9. All spires are to be mounted at the inlet of the wind tunnel just downstream of the honeycomb screen and arranged symmetrically. The central axis of the very middle spire should match that of the wind tunnel and the center-to-center lateral spacing between the two adjacent spires should be 0.36 m.
Table 3.1 Details of designing spires

<table>
<thead>
<tr>
<th>Description</th>
<th>5 Spires</th>
<th>3 Spires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of working section (mm)</td>
<td>1820</td>
<td>1820</td>
</tr>
<tr>
<td>Height of working section (mm)</td>
<td>1820</td>
<td>1820</td>
</tr>
<tr>
<td>Number of spires, $N_s$</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Center-to-center spacing between adjacent spires (mm)</td>
<td>364</td>
<td>607</td>
</tr>
<tr>
<td>Height of spires, $h_s$ (mm)</td>
<td>728</td>
<td>1200</td>
</tr>
<tr>
<td>The $\alpha$ value of the simulated terrain type</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>The boundary layer thickness, $\delta=0.72\times[(1+\alpha/2)*h_s]$ (mm)</td>
<td>611</td>
<td>995</td>
</tr>
<tr>
<td>$\beta = \delta \frac{\alpha}{H (1+\alpha)}$</td>
<td>0.08</td>
<td>0.14</td>
</tr>
<tr>
<td>$\psi = \beta \left(\frac{2}{1+2\epsilon} + \beta - \frac{x_0}{h_s \epsilon (1+\alpha)(1+\alpha/2)}\right) \sqrt{(1-\beta)^2}$</td>
<td>0.10</td>
<td>0.21</td>
</tr>
<tr>
<td>The floor friction coefficient, $G_f=0.136\left(\frac{\alpha}{1+\alpha}\right)^2$</td>
<td>0.00837</td>
<td>0.00837</td>
</tr>
<tr>
<td>The distance downstream of the spires, $X_0 = 6h_s$ (mm)</td>
<td>4368</td>
<td>7280</td>
</tr>
<tr>
<td>The total frontal area of the spires, $A_s=\frac{\psi \rho a c_{de}}{(1+\psi)c_{de}}$ (mm$^2$)</td>
<td>201544.2</td>
<td>349013.0</td>
</tr>
<tr>
<td>The frontal area of a single spire, $A = A_s/N_s$ (mm$^2$)</td>
<td>40308.8</td>
<td>69802.6</td>
</tr>
<tr>
<td>The base width of the spire, $b_s = 2A/h_s$ (mm)</td>
<td>110</td>
<td>190</td>
</tr>
</tbody>
</table>

Table 3.2 Dimensions of the designed spires (mm)

<table>
<thead>
<tr>
<th>Description</th>
<th>3-spire</th>
<th>5-spire</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_s$</td>
<td>1200</td>
<td>730</td>
</tr>
<tr>
<td>$b_s$</td>
<td>190</td>
<td>110</td>
</tr>
<tr>
<td>c</td>
<td>650</td>
<td>450</td>
</tr>
<tr>
<td>d</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>e</td>
<td>100</td>
<td>65</td>
</tr>
</tbody>
</table>
3.2.2 Design of roughness elements

The roughness element is also widely used as the passive device for simulating ABL in the wind tunnel. It is mainly used to correct the bottom part of the wind velocity profile and refine the simulated ABL in the wind tunnel.

Researchers commonly use the cubic shape roughness elements in the wind tunnel and it is suggested that the cubic height should be between \( \delta/16 \) and \( (h_s - \delta) \), where \( \delta \) is the thickness of the generated boundary layer in the wind tunnel and \( h_s \) is the height of the spire (Sill, 1988; Gartshore and Croos, 1995; Xu, 2007). Bai (2015) designed the wooden roughness element, the size of which is 60 mm, i.e. roughly 1/16 of the generated boundary layer.
boundary layer thickness. Two D43-N52 magnets are installed at the two diagonal corners of the floor surface, as shown in Figure 3.10. The magnets are used to secure the roughness elements at the arranged location during tests.

![Figure 3.10 The bottom surface of cubic roughness element with two magnets](image)

### 3.3 Experimental data analysis

Two types of signal analyses will be utilized in this study, i.e. the time-averaged analysis and the spectral analysis. The time-averaged analysis will be applied to estimate the flow velocity, the turbulence intensity and the integral length scale, whereas the spectral analysis will be used to understand how energy contained in the simulated ABL is distributed over the frequency band. The sampling frequency $SF$ and the required sampling number $N$ for hot-wire anemometer measurement should meet the requirement of these two types of data analysis.
For the time-averaged analysis, the sampling frequency \( SF \) is determined by the integral time scale \( T_1 \). The sampling time between the two consecutive samples is at least two times longer than the integral time scale of the velocity fluctuation under the condition of uncorrelated samples (Shannon, 1949). The requirement of sampling frequency \( SF \) can be obtained by (Jorgensen, 2002):

\[
SF \leq \frac{1}{2T_1}
\]  

(3.15)

and

\[
T_1 = \int_0^\infty \rho_X(\tau) d\tau
\]  

(3.16)

where \( \rho_X(\tau) = R_x(\tau)/R_x(0) \) is the auto-correlation coefficient of the samples; \( R_x(\tau) \) is the autocorrelation function, which is defined as

\[
R_x(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T x(t)x(t+\tau)dt
\]  

(3.17)

where \( x(t) \) is the long time series sampled according to the Nyquist criteria.

For spectral analysis, the sampling frequency is related to the cut-off frequency of the CTA. The requirement of the sampling frequency can be written as:

\[
SF \geq 2 * f_{cut-off}
\]  

(3.18)

where \( f_{cut-off} \) is the cut-off frequency of a low-pass filter in the CTA. The default cut-off frequency of the mini-CTA used in this study is 10 kHz.

After considering the requirements of both the time-averaged analysis and the spectral analysis, the sampling frequency of 32 kHz will be used for the hot-wire anemometer measurement.
In order to ensure obtaining stable results from hot-wire anemometer measurement, sensitivity analysis was conducted to determine the minimum required number of samples based on a sampling frequency of 32 kHz. The results of sensitivity analysis for mean wind velocity and standard deviation are shown in Figure 3.11 (a) and (b), respectively. The raw data points of both the mean value and the standard deviation of the wind velocity time history are not stable until the sampling number reaches 2293760, which, for a sampling frequency of 32 kHz, corresponds to a sampling time of 70s. Therefore, a sampling time of 70s is used for the hot-wire measurement.

(a) Sensitivity analysis for the mean wind velocity
(b) Sensitivity analysis for the standard deviation

Figure 3.11 Sensitivity analysis of the hot-wire anemometer at sampling frequency of 32 kHz

Flow properties are calculated from the signals collected by the DAQ. The Matlab® codes are developed to analyze these data as shown in Appendix C.
CHAPTER 4 EXPERIMENTAL RESULTS

In this chapter, the flow properties of the empty wind tunnel will be evaluated first. Then the previous results of ABL simulation, such as the effect of the spires, the roughness elements, and the spires combined with roughness elements, on the properties of the simulated ABL in the open-loop wind tunnel will be presented.

4.1 Flow properties in empty wind tunnel

The air flow in the wind tunnel is generated by 7-blade axial flow fan, which is controlled by a 60 horsepower AC motor. The relationship between the motor frequency and the generated streamwise flow velocity is shown in Figure 4.1. After applying linear regression, the relation between the two can be expressed as

\[ U = 0.25f_m \]  (4.1)

where \( U \) is the mean streamwise wind velocity in the wind tunnel and \( f_m \) is the motor frequency.

Figure 4.1 Relationship between motor frequency and generated mean wind velocity
To quantify the variation of the mean streamwise wind velocity and the turbulence intensity over the testing section, the profile of them along both the vertical and the horizontal directions need to be measured at multiple locations across the test section. These can be used to evaluate the uniformity and symmetry of the air flow field in the wind tunnel.

The measurement of flow properties was conducted using a Dantec Dynamic® 55P16 hot-wire anemometer mounted on the traverse system in the test section. The voltage signals were collected by the hot-wire anemometer, recorded by the data acquisition system and then processed by the developed Matlab® codes. The frequency of the motor was set at 48 Hz, which, based on Eq. (4.1), gave an estimated mean streamwise wind velocity of 12 m/s. The sampling frequency was 32 kHz and the sampling time was 70 s. The coordinate system of the test section in wind tunnel is shown in Figure 4.2. The X-axis is along the direction of flow in the wind tunnel, the Y-axis is in the horizontal and perpendicular to the flow direction, and the Z-axis is along the vertical direction. The origin is at the center of the turn table, as shown in Figure 4.2.
Five measurement locations were chosen to test the variation of flow properties along the vertical direction. They were located respectively at $Y=\pm500$ mm, $\pm250$ mm, $0$ mm, $+250$ mm and $+500$ mm. There were 15 measurement points, covering a range of $Z=5$ mm to $Z=1105$ mm, in each vertical profile curve. From $Z=5$ mm to $Z=305$ mm, the spacing between the two adjacent measurement points was 50 mm, and from $Z=305$ mm to $Z=1105$ mm, the spacing was 100 mm, as shown in Figure 4.3.
The mean wind velocity is obtained by averaging the measured wind velocity time history at any specific measurement location, which can be written as

$$\bar{U} = \frac{\sum_{i=1}^{N_s} U_i}{N_s} \quad (4.2)$$

where $U_i$ is the streamwise wind velocity and $N_s$ is the sampling number.

When computing the turbulence intensity according to Eq. (2.5), it was found that the turbulence intensity is around 3%, which is not reasonable for an empty wind tunnel. To find out the reason, a 10-minute streamwise wind velocity time history was collected in the empty wind tunnel and shown in Figure 4.4. Results in the figure suggest that the mean streamwise wind velocity has a low frequency variation with respect of time, i.e. the mean wind velocity is not a constant. Though this low frequency variation of mean wind velocity
can be neglected if the sampling time is long enough, in the current study, the sampling time is 70 s so the effect of this mean velocity variation should be considered. Since the turbulence intensity represents the fluctuation of the instantaneous wind velocity about the mean value, it is more reasonable to compute the turbulence intensity in this case with reference to the local mean wind velocity. This is achieved by dividing the entire sampled wind velocity time history into numerous shorter segments of 10 seconds, calculate the turbulence intensity of each segment using Eq. (2.5) based on the mean wind velocity within that time segment, then average the turbulence intensity of all the time segments to obtain the overall turbulence intensity.

![Figure 4.4 Low frequency variation of mean wind velocity in the empty wind tunnel](image)

A plot of the resulting mean streamwise velocity distribution is shown in Figure 4.5 (a) and followed by the variation of the turbulence intensity along the vertical directions, as shown in Figure 4.5 (b).

By inspection of the mean streamwise wind velocity vertical profiles in Figure 4.5 (a),
it may be noted that the mean streamwise wind velocity data coincide well at the same Z location for all five vertical profiles. Besides Z=5 mm and 55 mm, which are very close to the tunnel floor, the maximum percentage difference between the velocity data and the average of all five mean wind velocity values at the same height is less than 1.84%, as shown in Table 4.1.

The vertical profiles of the turbulence intensity $I_u$ at the five measurement locations are shown in Figure 4.5 (b). The average turbulence intensity in the empty wind tunnel is about 0.3% beyond the height of 200 mm above the tunnel floor and the maximum difference of turbulence intensity between the data at the same height is less than 0.4%, excluding the point at Z=+5 mm. The results in Figure 4.5 indicate that the flow field at the test section of the empty wind tunnel has good symmetry.

It can also be seen from Figure 4.5(a), the vertical profiles of the mean streamwise wind velocity that a turning point appears at about Y=205 mm above the wind tunnel floor in the vertical profiles of the stream wise wind velocity, above which the wind speed remains at roughly 11.6 m/s, which is close to the free-stream velocity. So, the boundary layer thickness is approximately 200 mm in depth.
Figure 4.5 Vertical profiles of mean streamwise wind velocity $U$ and turbulence intensity $I_u$ in the empty wind tunnel.
Table 4.1 The raw data of mean streamwise wind velocity profiles at Y= 0 mm, ±250 mm, ±500 mm in the empty wind tunnel (m/s)

<table>
<thead>
<tr>
<th>Height (mm)</th>
<th>Y= -500 mm</th>
<th>Y= -250 mm</th>
<th>Y= 0 mm</th>
<th>Y= +250 mm</th>
<th>Y= +500 mm</th>
<th>max. percentage difference * (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6.39</td>
<td>5.95</td>
<td>5.68</td>
<td>5.94</td>
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<td>5.37</td>
</tr>
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<td>55</td>
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<td>9.02</td>
<td>9.24</td>
<td>9.29</td>
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</tr>
<tr>
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<td>10.70</td>
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<td>10.53</td>
<td>10.57</td>
<td>10.64</td>
<td>0.51</td>
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<td>11.20</td>
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<td>11.36</td>
<td>11.38</td>
<td>0.71</td>
</tr>
<tr>
<td>255</td>
<td>11.54</td>
<td>11.34</td>
<td>11.36</td>
<td>11.33</td>
<td>11.36</td>
<td>0.26</td>
</tr>
<tr>
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<td>11.40</td>
<td>11.43</td>
<td>11.32</td>
<td>0.23</td>
</tr>
<tr>
<td>405</td>
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<td>11.43</td>
<td>11.43</td>
<td>11.44</td>
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<td>11.50</td>
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<td>0.09</td>
</tr>
<tr>
<td>605</td>
<td>11.61</td>
<td>11.64</td>
<td>11.45</td>
<td>11.40</td>
<td>11.34</td>
<td>0.34</td>
</tr>
<tr>
<td>705</td>
<td>11.66</td>
<td>11.62</td>
<td>11.41</td>
<td>11.31</td>
<td>11.59</td>
<td>0.94</td>
</tr>
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<td>11.31</td>
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<td>0.37</td>
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<td>11.37</td>
<td>11.59</td>
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<td>1.84</td>
</tr>
</tbody>
</table>

* The max. percentage difference is the max. absolute value of the difference between each velocity and the average value of these five sets of data at the same height, divided by the average of these five sets of data.

To quantify the horizontal variations of the mean streamwise wind velocity and turbulence intensity in the empty wind tunnel, three measurement locations were chosen to test flow properties in the horizontal direction. They were located at Z=+600 mm, +900 mm and +1200 mm. There were 26 measurement points in each horizontal profile curve. In between Y= -905 mm and Y= -605 mm as well as Y=505 mm and Y=905 mm, the spacing between the two adjacent measurement locations was 50 mm; whereas from Y= -605 mm to Y=505 mm, the spacing was 100 mm, as shown in Figure 4.6.
Figure 4.6 Locations of test lines along Z-axis

Figure 4.7 gives the horizontal profiles of both mean streamwise wind velocity $U$ and turbulence intensity $I_u$ in the empty wind tunnel. As can be seen from Figure 4.7(a) that the three horizontal profiles agree well with each other and have the same pattern, which means the flow field at the test section of the empty wind tunnel has good uniformity. The turning points on the three profile curves all appear at $Y=\pm 705$ mm, which suggests the boundary layer thickness is roughly 200 mm. The same boundary layer thickness can be observed from the horizontal profile of turbulence intensity $I_u$ in Figure 4.7(b). Beyond the boundary layer, the maximum percentage difference of the mean streamwise velocity data for all three horizontal profiles at the same $Y$ location is 1.43%, which occurs at $Y=+655$ mm. With the effect of the boundary layer, the maximum percentage difference is higher. It is 2.65% at $Y=+905$ mm, as shown in Table 4.2. There is a “bump” in three horizontal mean
streamwise wind velocity profiles at $Y=-105$ mm, where the mean wind velocity is slightly lower than the free stream velocity. The reason of it is that the hot-wire anemometer was flipped to the other side at this location in order to collect the voltage data at $Y=-905$ mm because of the limitation of the Z-rod on the traverse system.

(a) Horizontal profiles of mean streamwise wind velocity $U$
Based on the above experimental results of the typical flow characteristics, such as the vertical and the horizontal variation of mean streamwise wind velocity $U$ and the turbulence intensity $I_u$, it can be concluded that the flow field at the test section of the empty wind tunnel has good symmetry and uniformity in both vertical and horizontal directions. The boundary layer thickness of the empty wind tunnel is approximately 200 mm, which is identified from the pattern of both the vertical and the horizontal profiles of the mean streamwise wind velocity $U$ and turbulence intensity $I_u$. 
Table 4.2 The raw data of mean streamwise wind velocity profiles at Z= +600 mm, +900 mm, +1200 mm in the empty wind tunnel (m/s)

<table>
<thead>
<tr>
<th>Y (mm)</th>
<th>Z= 600 mm</th>
<th>Z= 900 mm</th>
<th>Z=1200 mm</th>
<th>max. percentage difference * (%)</th>
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</thead>
<tbody>
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<td>1.07</td>
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<td>10.82</td>
<td>10.57</td>
<td>2.11</td>
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<td>8.92</td>
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<td>5.69</td>
<td>5.92</td>
<td>5.91</td>
<td>2.64</td>
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</tbody>
</table>

* The max. percentage difference is the max. absolute value of the difference between each velocity and the average value of these three sets of data at the same height, divided by the average of these three sets of data.
4.2 Effect of passive ABL simulation devices on the flow characteristics

In this section, the profiles of mean streamwise wind velocity and turbulence intensity along the vertical direction resulting from the introduction of various passive simulation devices will be presented. The effect of spires, roughness elements and the spires combined with roughness elements on ABL simulation in wind tunnel will be discussed. The details of all the testing cases are listed in Table 4.3.

Table 4.3 Details of the testing cases to study the effect of different passive ABL simulation devices

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Spires number</th>
<th>Roughness element</th>
<th>Total number</th>
<th>Array arrangement type</th>
<th>Longitudinal spacing (mm)</th>
<th>Lateral spacing (mm)</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
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<tr>
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<td>40 × 10</td>
<td>Aligned</td>
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<td>180</td>
</tr>
<tr>
<td>5</td>
<td>N/A</td>
<td>200</td>
<td>20 × 10</td>
<td>Staggered</td>
<td>360</td>
<td>180</td>
</tr>
</tbody>
</table>

4.2.1 Effect of spires

The spires, both the 5-spire and the 3-spire cases, designed in the previous chapter, were mounted at the inlet of the flow development region of the wind tunnel. The central axis of the very middle spire should match that of the wind tunnel. For the 5-spire and 3-spire cases, the center to center spacing between the two adjacent spires were 0.36 m and 0.6 m, respectively. The actual layout of the 3-spire case set-up is shown in Figure 4.8.
Figures 4.9 (a) and (b) give the vertical profiles of the mean streamwise wind velocity profile $U$ and the turbulence intensity $I_u$ for Case 1 (5-spike) and Case 2 (3-spike), respectively. By inspection, if 5 spires were installed, when the height is beyond 605 mm above the wind tunnel ground, the mean streamwise wind speed remains at about 12.3 m/s. The turning point of the turbulence intensity $I_u$ vertical profile for Case 1 (5-spike) at the same height can also be found in Figure 4.9 (b), which clearly indicates that the boundary layer thickness generated by 5 spires is about 605 mm. This agrees well with prediction by the Irwin’s approach shown in Table 3.1. For Case 2 (3-spike), the vertical profiles of both mean streamwise wind velocity $U$ and the turbulence intensity $I_u$ show that the turning point occur at the height of about 955 mm, which also agrees with the prediction in Table
3.1. This set of results confirms that in order to generate different atmospheric boundary layer thickness in the wind tunnel to satisfy the needs of different models scales, different spire size should be used. In addition, it proves that the spire design according to the Irwin’ method was successful.

Figure 4.9 (c) depicts the dimensionless vertical profile of mean streamwise wind velocity for both Case 1 and Case 2. The height is normalized by the boundary layer thickness and the mean streamwise wind velocity is normalized by the free-stream velocity. From the figure, the power-law curve fitting exponent $\alpha$ for both the 5-spire and 3-spire cases are 0.14. It is less than the power-law curve profile exponent $\alpha$ of the terrain type “A”, which is 0.33.
Figure 4.9 Effect of spire number on the flow characteristics (Case 1 and Case 2)

(b) Vertical profile of turbulence intensity $I_u$

(c) Dimensionless vertical profile of mean streamwise wind velocity
4.2.2 Effect of roughness elements

To study the effect of roughness elements on the characteristics of the generated air flow in the wind tunnel, two factors need to be considered, i.e. the number of roughness elements and their layout.

Two cases were tested and the details of them are shown in Table 4.4. The direction of the roughness elements column is defined to be the direction parallel with X-axis, which is along the longitudinal direction of the wind tunnel. And the direction of the roughness elements row is along the Y-axis.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Roughness elements number</th>
<th>Array (Row × Column)</th>
<th>Longitudinal spacing (mm)</th>
<th>Lateral spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>200</td>
<td>20 × 10</td>
<td>360</td>
<td>180</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>40 × 10</td>
<td>180</td>
<td>180</td>
</tr>
</tbody>
</table>

For example, in Case 3, the number of roughness elements is 200 pieces and the array of them is 20 rows × 10 columns, which covered a wind developing zone with a length of 7200 mm and a width of 1800 mm. So the average influence zone of each roughness element is 7200/20=360 mm in length and 1800/10=180 mm in width. Figure 4.10 shows a fraction of the roughness elements arrangement in Cases 3 and 4. The actual layout of Case 3 in the wind tunnel is given in Figure 4.11.
Figure 4.10 Schematics of roughness element layout in Case 3 and Case 4 (partial) (unit: mm)
It can be identified from Figure 4.12, the thickness of the boundary layer generated by the roughness elements is around 400 mm for both Case 3 and Case 4. Since the height of the roughness elements used in this study is 60 mm, the boundary layer thickness is thus roughly 6.5 times the height of the roughness elements. The results of Xin (2006) and Xu (2010) showed that the height the roughness elements could influence was about 5 times the roughness elements height.

It is worth noting that the mean wind velocity of Case 4 (400 roughness elements case) is less than that of Case 3 (200 roughness elements case) at the same height when the measurement location is below 400 mm in the wind tunnel. The reason of which should be the difference in the number of roughness elements. The blockage of the area due to the roughness elements in Case 4 is larger than that in Case 3, which would further decrease the
wind velocity. The wind velocity remains as a constant beyond the boundary layer.

Figure 4.12 Effect of roughness element number on the vertical profiles of mean streamwise wind velocity $U$ (Case 3 and Case 4)

Other factor that may influence the flow characteristics is the layout of the roughness elements. Two scenarios were chosen to study the effect of the roughness element arrangement, the first scenario was Case 3, whereas the second scenario is the staggered arrangement of 200 roughness elements and the arrangement of roughness elements for the second scenario (Case 5) is shown in Figure 4.13. The details of them are shown in Table 4.5.
Table 4.5 Details of the cases to study the effect of roughness element arrangement

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Number of roughness elements</th>
<th>Array (Row × Column)</th>
<th>Arrangement type</th>
<th>Longitudinal spacing (mm)</th>
<th>Lateral spacing (mm)</th>
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<td>20 × 10</td>
<td>Aligned</td>
<td>360</td>
<td>180</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>20 × 10</td>
<td>Staggered</td>
<td>360</td>
<td>180</td>
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</tbody>
</table>

Figure 4.13 Layout of roughness elements for Case 5 (staggered) (unit: mm)

Figure 4.14 shows the effect of roughness element layout on the vertical profile of mean wind velocity $U$ for Case 3 (aligned) and Case 5 (staggered). The turning points in Case 3 and Case 5 both appear at the height of around 400 mm above the wind tunnel floor, which is roughly 6.5 times of the height of the roughness element.

In Figure 4.14, the mean wind velocity of Case 5 (staggered) is less than that of Case 3 (aligned) at the same height when the height is below 400 mm in the wind tunnel. This is
because the staggered arrangement of roughness elements would block more area of the test cross section than the aligned arrangement, which would further reduce the wind velocity.

Figure 4.14 Effect of roughness elements layout on vertical profiles of mean streamwise wind velocity $U$ (Case 3 and Case 5)

Based on the above discussion, increasing the number and staggering the layout of the roughness elements (increasing the blockage area) will cause the decrease of the mean streamwise wind velocity. These methods can be used to adjust the simulation of terrain condition.
4.3 Simulation results

Among various passive simulation devices, using triangular shape spires combined with roughness elements is one of the most common choices to simulate ABL in wind tunnel. The triangular spires serve as eddy generators and the roughness elements are mainly used to refine the simulated ABL by correcting the bottom part of the wind velocity profile. Based on the objectives of this study, terrain types “A” and “B” will be simulated using both 3 spires and 5 spires combined with roughness elements. The naming convention of the case ID is illustrated in Figure 4.15.

![Figure 4.15 The naming convention of the case ID](image)

4.3.1 Simulated ABL in terrain type “A”

4.3.1.1 Three spires combined with roughness elements

Case 3S0-20R10CA1 and Case 3S0-40R10CA1 were tested to study the effect of 3 spires combined with roughness elements on the flow characteristics. The difference between these two cases is the number of the roughness elements that utilized in the simulation. The details of the layout are given in Table 4.6. Figure 4.16 shows a sample...
layout of Case 3S0-20R10CA1 (3 spires combined with 200 roughness elements) in the wind tunnel.

Table 4.6 Details of the cases to study the effect of different numbers of roughness elements (The difference between 200 REs and 400 REs)

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Number of spires</th>
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<th>Influence area (mm)</th>
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<td>360 × 180</td>
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<td>180 × 180</td>
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</table>

Figure 4.16 Layout of Case 3S0-20R10CA1 (3 spires combined with 200 roughness elements) in the wind tunnel

Figure 4.17 (a) shows the dimensionless vertical profiles of mean streamwise wind velocity of Case 3S0-20R10CA1 and Case 3S0-40R10CA1, and the power-law profile of the target terrain type “A” with ρ=0.33. The boundary layer thickness is defined as the height above the ground where the sampled mean streamwise wind velocity $U$ differs less
than 1% from the free-stream velocity and the ABL thickness of both Case is 955 mm. Curve fitting is applied to the dimensionless vertical profile of streamwise wind speed of Case 3S0-20R10CA1 and Case 3S0-40R10CA1, and the power-law exponent $\alpha$ of them are 0.25 and 0.29, respectively. According to the power-law exponent, the $\alpha$ value of Case 3S0-40R10CA1 agrees better with the requirement of terrain type “A”, which is 0.33. Within the generated ABL, the dimensionless wind velocity obtained in both cases is slightly larger than that of the target power-law profile.

Figure 4.17 (b) depicts the vertical profile of the turbulence intensity $I_u$. Within the boundary layer thickness, the difference of the turbulence intensity between the two cases decreases along the increasing height. After reaching the top of the generated boundary layer, $Z=955\text{mm}$, it can be observed that $I_u$ in both cases remains as a constant. The profile of Walshe is based on the empirical formula, Eq. (2.11), when $K=0.015$ (Walshe, 1973), which corresponds to a power-law exponent of $\alpha=0.28$. The turbulence intensity of both cases are less than that predicted by the Walshe empirical formula when the height is 200 mm above the wind tunnel floor.

Figure 4.17 (c) depicts the vertical profile of integral length scale for Case 3S0-20R10CA1 and Case 3S0-40R10CA1. Within the generated boundary layer, the integral length scale of both cases increase along the increasing height. The empirical profile suggested by Cook (1978) is derived based on Eq. (2.16). As shown in Figure 4.17 (c), the Cook’s empirical profile for $z = 2.0$, corresponding to the terrain type “A”, can be
used to evaluate the integral length scale profile. It is observed that when the height is beyond 600 mm above the wind tunnel floor, the integral length scales in Case 3S0-20R10CA1 and 3S0-40R10CA1 are much larger than those predicted by Cook’s empirical profile (1978).

To resolve the problem of inadequate turbulence intensity in the middle and upper part of the generated boundary layer, two approaches have been used. One is to modify the spire shape by attaching a piece of rectangular board to the upper part of the regular spires, and the other is to use double-height roughness elements (as shown in Figure 4.18).

(a) Vertical profile of dimensionless mean streamwise wind velocity
Figure 4.17 Effect of 3 spires combined with different numbers of roughness elements on the flow characteristics of the generated ABL (Case 3S0-20R10CA1 and 3S0-40R10CA1)

(b) Vertical profile of turbulence intensity $I_u$

(c) Integral length scale $L_u$
In order to study the effect of the modified spires, Case 3S0-40R10CA1, 3S9-40R10CA1 and 3S12.5-40R10CA1 have been tested to study the effect of the modified spires. The details are shown in Table 4.7.

![Schematic of modified spires and double-height roughness element](image)

Figure 4.18 Schematic of modified spires and double-height roughness element

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Spire</th>
<th>Roughness element</th>
<th>Number</th>
<th>( b_{board}(\text{cm}) )</th>
<th>Total number</th>
<th>Array (Row × Column)</th>
<th>Influence area (( \text{mm}^2 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>3S0-40R10CA1</td>
<td>3</td>
<td></td>
<td>0</td>
<td>400</td>
<td>40 × 10</td>
<td>180 × 180</td>
<td></td>
</tr>
<tr>
<td>3S9-40R10CA1</td>
<td>3</td>
<td></td>
<td>9</td>
<td>400</td>
<td>40 × 10</td>
<td>180 × 180</td>
<td></td>
</tr>
<tr>
<td>3S12.5-40R10CA1</td>
<td>3</td>
<td></td>
<td>12.5</td>
<td>400</td>
<td>40 × 10</td>
<td>180 × 180</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.19 shows the vertical profile of the dimensionless mean streamwise wind velocity and the turbulence intensity \( I_u \) for Case 3S0-40R10CA1, 3S9-40R10CA1 and
3S12.5-40R10CA1. The difference among these three cases are the width of the rectangular board added at the top part of the modified spires, and the width of these three cases are 0 cm, 9 cm and 12.5 cm, respectively. As can be seen from Figure 4.19 (a), the dimensionless velocity vertical profile for Case 3S12.5-40R10CA1 show better results than that of Case 3S0-40R10CA1 and 3S9-40R10CA1. After applying curve fitting to these three sets of mean wind velocity data, the power-law exponent α of them are 0.29, 0.30 and 0.33, respectively. The simulation results of Case 3S12.5-40R10CA1 match the requirement of terrain type “A” with α=0.33 within the boundary layer.

Figure 4.19 (b) shows the vertical profile of the turbulence intensity $I_u$. Because of the effect of rectangular board added at the top part of the spires, the difference among the turbulence intensity of Case 3S0-40R10CA1, 3S9-40R10CA1 and 3S12.5-40R10CA1 is clear from the figure. When compared with Case 3S0-40R10CA1 and 3S9-40R10CA1, the turbulence intensity of Case 3S12.5-40R10CA1 agrees better with the Walshe’s empirical profile at the same height, especially for the measurement points beyond the height of 600 mm. The reason of it should be that the board of the spires increases the blockage of the area in the upper part of the spires, which increases the turbulence intensity. So the spires with 12.5 cm board work well and are used to simulate the boundary layer in the following tests.
Figure 4.19 Effect of board of 3 modified spires combined with roughness elements on the flow characteristics of the generated ABL (Cases 3S0-40R10CA1, 3S9-40R10CA1 and 3S12.5-40R10CA1)

(a) Vertical profile of dimensionless mean streamwise wind velocity

(b) Vertical profile of turbulence intensity $I_u$
It can be seen that the effect of the modified spires is better than that of original spires on the turbulence intensity profile of the generated boundary layer. But for the measurement locations above 200 mm from the tunnel floor, the magnitude of the turbulence intensity is still not enough to match the empirical formula (Walshe, 1973). Based on the study of how single-height roughness elements would affect the flow characteristics, double-height roughness elements may influence the turbulence intensity at higher locations. So in the second approach of improving the turbulence intensity simulation, double-height roughness elements are used. Two cases have been tested, Case 3S12.5-40R10CA1 and 3S12.5-20R10CA2, and the details of them are given in Table 4.8.

Table 4.8 Details of the cases to study the effect of double-height roughness elements

<table>
<thead>
<tr>
<th>Spire Case ID</th>
<th>Number</th>
<th>( b_{board} ) (cm)</th>
<th>Total number</th>
<th>Type</th>
<th>Array (Row x Column)</th>
<th>Influence area (( mm^2 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>3S12.5-40R10CA1</td>
<td>3</td>
<td>12.5</td>
<td>400</td>
<td>Single</td>
<td>40 x 10</td>
<td>180 x 180</td>
</tr>
<tr>
<td>3S12.5-20R10CA2</td>
<td>3</td>
<td>12.5</td>
<td>400</td>
<td>Double</td>
<td>20 x 10</td>
<td>360 x 180</td>
</tr>
</tbody>
</table>

Figure 4.20 depicts the vertical profiles of dimensionless mean streamwise wind velocity and turbulence intensity \( I_u \) for Case 3S12.5-40R10CA1 and 3S12.5-20R10CA2 to study the effect of the double-height roughness elements. After curve fitting of these two sets of mean wind velocity profiles, the alpha values are 0.33 and 0.36, respectively. From Figure 4.20 (a), the data in Case 3S12.5-20R10CA2 are more agreeable with the target power-law profile when compared with that of Case 3S12.5-40R10CA1 for the measurement points within the range between the dimensionless height of 0.2 and 1.0,
which means the effect of double-height roughness element arrangement is better than that of the single-height roughness element on simulating atmospheric boundary layer in the wind tunnel from the perspective of mean wind velocity profile.

Figure 4.20 (b) shows the vertical profiles of turbulence intensity for Case 3S12.5-40R10CA1 and 3S12.5-20R10CA2. For the measurement locations below the height of 600 mm, the turbulence intensity of the double-height roughness element case is larger than that of the single-height roughness element. The values of turbulence intensity for these two cases coincide well with each other once beyond Z=600 mm. It matches the results of Xin (2010), which found that the roughness elements could influence the flow properties within 5 times of the roughness element height above the ground. So the approach of double-height roughness element arrangement can be used to increase the turbulence intensity of the middle and the bottom part of the generated atmospheric boundary layer.
(a) Vertical profile of dimensionless mean streamwise wind velocity

(b) Vertical profile of turbulence intensity $I_u$

Figure 4.20 Effect of double-height roughness elements combined with 3 modified spires on the flow characteristics of the generated ABL (Cases 3S12.5-40R10CA1 and 3S12.5-20R10CA2)
The effects of spires with board and double-height roughness elements have been studied. Results show that both can help to improve the flow characteristics of the generated atmospheric boundary layer, especially for the middle part of the turbulence intensity profile. So two cases, Case 3S12.5-20R10CA2 and 3S12.5-12R10CS2, have been tested by applying the modified spires combined with double-height roughness elements. The details of them are given in Table 4.9.

Table 4.9 Details of the cases to study the effect of roughness element arrangement type using 3 modified spires combined with roughness elements

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Spire Number</th>
<th>(b_{board}) (cm)</th>
<th>Total number</th>
<th>Array (Row × Column)</th>
<th>Influence area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3S12.5-20R10CA2</td>
<td>3</td>
<td>12.5</td>
<td>400</td>
<td>20 × 10</td>
<td>360 × 180</td>
</tr>
<tr>
<td>3S12.5-12R10CS2</td>
<td>3</td>
<td>12.5</td>
<td>240</td>
<td>12 × 10</td>
<td>600 × 180</td>
</tr>
</tbody>
</table>

Figure 4.21 (a) shows the vertical profile of dimensionless mean streamwise wind velocity for Case 3S12.5-20R10CA2 and 3S12.5-12R10CS2, and the difference between them is the roughness element arrangement type, aligned or staggered. Curve fitting is applied to the vertical profile of mean streamwise wind velocity profile, the power-law exponent \(\alpha\) are 0.36 and 0.35, respectively. From the figure, the curve of Case 3S12.5-12R10CS2 is slightly more agreeable with the target power-law wind speed profile within the boundary layer thickness when compared with that of Case 3S12.5-20R10CA2, especially for the location below dimensionless height of 0.2.

Figure 4.21 (b) depicts the vertical profile of the turbulence intensity \(I_u\). When
compared with the aligned arrangement (Case 3S12.5-20R10CA2), the vertical profile of
turbulence intensity of the staggered arrangement (Case 3S12.5-12R10CS2) is more
agreeable with the Walshe’s empirical profile for the measurement locations below Z=400
mm.

(a) Vertical profile of dimensionless mean streamwise wind velocity
Based on Figure 4.21, the simulation result of Case 3S12.5-12R10CS2 is better than that of Case 3S12.5-20R10CA2 because the power-law exponent better represents the target terrain type and the turbulence intensity at the bottom part of ABL is more agreeable with the empirical formula profile. But the power-law exponent of 3S12.5-12R10CS2 is 0.35, which is still larger than the requirement of target terrain type “A” ($\alpha=0.33$). Based on the previous results of Figure 4.17 and 4.20, changing the arrangement and number of the roughness elements can influence the power-law exponent. More trials have been made to reduce the power-law exponent. And the case that can generate best simulation results is the Case 3S12.5-11R10CS2 and the vertical profiles of flow characteristics are shown in
The generated boundary layer thickness is 955 mm. After the curve fitting of mean streamwise wind velocity profile, the exponent $\alpha$ is 0.338, which agrees well with the requirement of the terrain type “A” with $\alpha=0.33$. It can be seen from Figure 4.22 (a) that all data points on the dimensionless mean streamwise wind velocity profile for Case 3S12.5-11R10CS2 match well with the target power-law velocity profile with $\alpha=0.33$.

Figure 4.22 (b) depicts the vertical profile of turbulence intensity $I_u$. One common issue of using passive simulation devices is that the turbulence intensity is inadequate at the middle and the upper part of the generated boundary layer. The trend of the simulated turbulence intensity vertical profile is similar to that predicted by the Walshe’s empirical formula (Walshe, 1973), Eq. (2.16), within the boundary layer thickness. As shown in Table 2.4, 3 different $K$ values are given corresponding to different power-law exponent $\alpha$ (Walshe, 1973). In the current study, $K=0.015$ is chosen to evaluate the simulation of turbulence intensity, which corresponds to a power-law exponent $\alpha=0.28$. For the simulation of atmospheric boundary layer of terrain type “A”, the requirement of power-law exponent is $\alpha=0.33$. If $\alpha$ increases from 0.28 to 0.33, the Walshe’s empirical curve would shift to high turbulence intensity, i.e. moves horizontally towards right, because the value of turbulence intensity will increase along with the increasing power-law exponent. For the measurement locations below $Z = 500$ mm, all the raw data points are more or less within the range between $\pm 25\%$ of the Walshe’s empirical formula for $\alpha=0.28$. 
For the measurement locations above \( Z = 500 \) mm, the turbulence intensity value of this set of data is close to the \(-25\%\) of the Walshe’s empirical formula. In the case of terrain type A, the corresponding atmospheric boundary layer thickness in full scale is 450m, whereas that simulated in the current study is 955mm. From the perspective of Model Law (Jensen, 1958), 955 mm in model scale stands for 450 m in the full scale, which indicates the model scale is about 1:470 for the simulation of terrain type “A” using 3 spires. Typically, buildings are under the height of 200 m in full scale and it can be scaled down to the height of about 425 mm in this model scale, the turbulence intensity within which is between \( \pm25\% \) of the Walshe’s empirical formula for \( \alpha=0.28 \).

Figure 4.22 (c) depicts the vertical profile of the simulated integral length scale. When compared with the empirical formula by Cook (1978), Eq. (2.17), all the raw data points are more or less within the range between \( \pm25\% \) of the Cook’s empirical formula for \( \alpha=0.33 \) within the boundary layer thickness.

Figure 4.22 (d) and (e) depict the power spectrum of the simulated atmospheric boundary layer in the log-log coordinates and the Monin coordinates, respectively. The measurement location at \( X=500 \) mm, \( Y=0 \) mm and \( Z=805 \) mm is selected as the sample location, which is close to the middle of the cross-section at the test section. From Figure 4.22 (d), the inertial sub-range can be observed between frequencies of about \( 10^2 \) and \( 10^3 \) Hz because the turbulent energy begins to dissipate clearly in this range (Counihan, 1975). The power spectral density follows a \(-5/3\) slope in the inertial subrange, satisfying
the Kolmogorov’s -5/3 Law (Kolmogorov, 1941), which is important from the perspective of structural analysis (Wittwer and Moller, 2000). When compared with the Von Kármán and the Kaimal power spectrums density function in Figure 4.22(e), it is clear that the simulated power spectrum is in good agreement with those empirical formulas.

(a) Vertical profile of dimensionless mean streamwise wind velocity (X=500 mm, Y=0 mm)
(b) Vertical profile of turbulence intensity $I_u$ (X=500 mm, Y=0 mm)

(c) Vertical profile of integral length scale $L_u^x$ (X=500 mm, Y=0 mm)
(d) Power spectrum in log-log coordinates (X=500 mm, Y=0 mm, Z=805 mm)

(e) Power spectrum in Monin coordinates (X=500 mm, Y=0 mm, Z=805 mm)

Figure 4.22 Flow characteristics of atmospheric boundary layer simulation for terrain type “A” by Case 3S12.5-11R10CS2
Based on the vertical profiles of the mean streamwise wind velocity, turbulence intensity and integral length scale, as well as the power spectrum, the flow characteristics of the simulated atmospheric boundary layer associated with terrain type “A” using 3 modified spires combined with 220 roughness elements (11 rows, 10 columns, double-height roughness elements, staggered) are considered satisfactory. The details and the layout of Case 3S12.5-11R10CS2 are given in Table 4.10 and Figure 4.23, respectively.

Table 4.10 Details of the final setup for the simulation of terrain type “A” using 3 modified spires combined with double-height roughness elements

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Spire</th>
<th>Roughness element</th>
<th>Total number</th>
<th>Type</th>
<th>Array (Row × Column)</th>
<th>Influence area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3S12.5-11R10CS2</td>
<td>3</td>
<td>12.5</td>
<td>220</td>
<td>Double</td>
<td>11 × 10</td>
<td>650 × 180</td>
</tr>
</tbody>
</table>

Figure 4.23 Details of the layout for the simulation of terrain type “A” (Case 3S12.5-11R10CS2)

4.3.1.2 Five spires combined with roughness elements

In order to accommodate the requirement of different model scales, terrain type “A”
should also be simulated using different number of spires combined with roughness elements, which lead to different thickness of generated atmospheric boundary layer. According to the design of the spires in Chapter 3, 5 spires are applied to simulated ABL of terrain type “A” in open-loop wind tunnel.

Based on the simulation experience in Section 4.3.1.1, the modified spires with rectangular board are used to simulate the atmospheric boundary layer in the following tests. For the simulation of terrain type “A” using 3 modified spires, the width of the board is 12.5 cm, which is 2/3 of the width of the spire base. In the case of 5 spires, the base of the spire is 11 cm. The rectangular board width is thus set as 11×2/3 ≈ 7 cm first. In order to check the effect of adding the rectangular board, two cases have been tested, with the details shown in Table 4.11.

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Spire Number</th>
<th>$b_{board}$ (cm)</th>
<th>Roughness element Number</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>5S0</td>
<td>5</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>5S7</td>
<td>5</td>
<td>7</td>
<td>0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Figure 4.24 depicts the vertical profiles of the dimensionless mean streamwise wind velocity and the turbulence intensity for Cases 5S0 and 5S7 to optimize the width of the rectangular board for the modified spires. After applying curve fitting to these two sets of mean wind velocity data, it gives the power-law exponent $\alpha$ are 0.14 and 0.16, respectively.
Figure 4.24 (b) shows the vertical profile of the turbulence intensity $I_u$. It can be seen from the Figure 4.24 that the effect of the rectangular board of the spires is clear. Once reach the height of 400 mm, the turbulence intensity of Case 5S7 becomes larger than that of Case 5S0 at the same height. Since the modified spires improve the turbulence intensity at the upper and middle part of the profile, the spires with 7 cm board are used to simulate the boundary layer in the following tests.

(a) Vertical profile of dimensionless mean streamwise wind velocity
In order to study the effect of the number of roughness elements, two cases have been tested by utilizing 5 modified spires combined with single-height roughness elements, and the details of these cases are shown in Table 4.12. Figure 4.25 gives a sample layout of Case 5S7-40R10CA1 (5 modified spires with 7 cm rectangular board combined with 400 roughness elements) in the wind tunnel.

Table 4.12 Details of the cases to study the effect of the number of roughness elements

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Spire</th>
<th>Roughness element</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>$b_{\text{board}}$ (cm)</td>
</tr>
<tr>
<td>5S7-30R10CA1</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>5S7-40R10CA1</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>
Figure 4.25 Layout of Case 5S7-40R10CA1 in wind tunnel

Figure 4.26 (a) shows the dimensionless vertical profile of mean streamwise wind velocity of Case 5S7-30R10CA1 and 5S7-40R10CA1, and the power-law profile of the target terrain type “A” with $\alpha = 0.33$. The generated boundary layer thickness is 705 mm. After applying curve fitting to these two sets of dimensionless mean streamwise wind speed profiles, it gives the power-law exponent $\alpha$ of 0.30 and 0.31, respectively. It can be seen from Figure 4.26 (a), for the middle part of the dimensionless wind velocity profiles, the wind speed obtained in both cases are larger than that of the power-law curve with $\alpha = 0.33$.

Figure 4.26 (b) depicts the vertical profile of the turbulence intensity $I_u$. Within the height of 300 mm above the tunnel floor, the difference of the turbulence intensity between the two cases decreases along the increasing height. And the turbulence intensity obtained in both cases agree well once above the height of $Z=300$ mm, which is 5 times of the
roughness element height. The turbulence intensity of both cases are considerably less than that predicted by Walshe’s empirical formula above the height of 200 mm. So the double-height roughness elements are used to increase the turbulence intensity at the bottom and the middle part of the generated ABL.

(a) Vertical profile of dimensionless mean streamwise wind velocity
Based on earlier results of the effect of the $b_{board}$ and number of single-height roughness elements in Figure 4.24 and 4.25, the 5 modified spires with 7 cm rectangular board are combined with double-height roughness elements in the simulation of atmospheric boundary layer associated with terrain type “A”. Three cases have been tested for studying the effect of double-height roughness element number and the details of these cases are described in Table 4.13. Figure 4.27 shows a sample layout of Case 5S7-20R10CA2 (5 modified spires with 7 cm board combined with 200 double-height roughness elements) in the wind tunnel.
Table 4.13 Details of the cases to study the effect of the number of double-height roughness elements

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Spire Number</th>
<th>(b_{board}) (cm)</th>
<th>Total number</th>
<th>Array (Row × Column)</th>
<th>Influence area ((mm^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>5S7-20R10CA2</td>
<td>5</td>
<td>7</td>
<td>400</td>
<td>20 × 10</td>
<td>360 × 180</td>
</tr>
<tr>
<td>5S7-10R10CA2</td>
<td>5</td>
<td>7</td>
<td>200</td>
<td>10 × 10</td>
<td>720 × 180</td>
</tr>
<tr>
<td>5S7-10R6CA2</td>
<td>5</td>
<td>7</td>
<td>120</td>
<td>10 × 6</td>
<td>720 × 300</td>
</tr>
</tbody>
</table>

Figure 4.27 Layout for Case 5S7-20R10CA2 in wind tunnel

Figure 4.28 depicts the vertical profile of the dimensionless mean streamwise wind velocity and the turbulence intensity \(I_u\) for Case 5S7-20R10CA2, 5S7-10R10CA2 and 5S7-10R6CA2. As can be seen from Figure 4.28 (a), the profile of Case 5S7-10R6CA2 is more agreeable with the power-law curve associated with terrain type “A”, especially for the range below the dimensionless height of 0.3 when compared with those of Case 5S7-20R10CA2 and 5S7-10R10CA2. After applying curve fitting to these three sets of mean streamwise wind velocity data, the power-law exponent \(\alpha\) of them are obtained to be 0.39, 0.37 and 0.31, respectively. However, the power-law exponent of target terrain
type “A” is 0.33. The power-law exponent $\alpha$ obtained in Case 5S7-10R6CA2 is slightly less than that of terrain type “A”.

Figure 4.28 (b) shows the vertical profile of the turbulence intensity $I_u$ of these three cases. In Figure 4.28 (b), once reaches the height of 450 mm above the tunnel floor, the turbulence intensity profiles match well with each other for all three cases. The reason of it should be the blockage of the upper part of the modified spires for three cases are the same. Below the height of 200 mm, the turbulence intensity values of both Cases 5S7-20R10CA2 and 5S7-10R10CA2 are much larger than that of the Walshe’s empirical profile associated with terrain type “A”. But for Case 5S7-10R6CA2, all the raw data points are agreeable with the empirical profile at the same height when compared with the other cases.

(a) Vertical profile of dimensionless mean streamwise wind velocity
Based on the results of Figure 4.28, Case 5S7-10R6CA2 gives the best results among the three cases in simulating atmospheric boundary layer associated with terrain type “A”, except the power-law exponent $\alpha$ of it is slightly less than the requirement of terrain type “A”. In order to improve the power-law exponent, more tests have been conducted by changing the number and arrangement type of the double-height roughness elements. The vertical profiles of flow characteristics of the generated ABL by the case which yields the best result among all, i.e. Case 5S7-10R6CS2 are shown in Figure 4.29.

After applying curve fitting to the vertical profile of the dimensionless mean streamwise wind velocity of Case 5S7-10R6CS2, the generated boundary layer thickness is
705 mm and the power-law exponent $\alpha$ is 0.325, which satisfies the requirement of the terrain type “A”. Figure 4.29 (a) shows the vertical profile of the dimensionless mean streamwise wind velocity of Case 5S7-10R6CS2 and the power-law profile of the target terrain type “A”.

Figure 4.29 (b) depicts the vertical profile of the turbulence intensity $I_u$ and the profile of Walshe’s empirical formula corresponding to $\alpha=0.28$. Results show that even by adding the rectangular board, turbulence intensity at the top part of the generated boundary layer is still less than the values predicted by Walshe’s empirical formula. For the height between 150 mm and 350 mm above the tunnel floor, the raw data points are within the range between $\pm25\%$ of Walshe’s empirical formula. For the measurement locations below $Z=150$ mm, the turbulence intensity is larger than the empirical formula with $\alpha=0.28$. Since the turbulence intensity empirical formula predicted by Walshe for terrain type “A” ($\alpha=0.33$) is larger than the profile associated with $\alpha=0.28$, the turbulence intensity of this case should be within the range of turbulence intensity profile associated with terrain type “A”.

Figure 4.29 (c) depicts the vertical profile of the integral length scale of Case 5S7-10R6CS2. It can be seen from Figure 4.29 (c), for the measurement locations between the height of 100 mm and 600 mm above the tunnel floor, all the raw data points agree well with the prediction by Cook’s empirical formula associated with terrain type “A” ($\alpha=0.33$).

Figure 4.29 (d) and (e) depict the power spectrum of the simulated atmospheric
boundary layer in the log-log coordinates and the Monin coordinates, respectively. The sample location is selected to be at X=500 mm, Y=0 mm and Z=355 mm, which is close to the middle height of the generated boundary layer at the test section. It can be seen from Figure 4.29(d), the energy begins to dissipate within the frequencies between $10^2$ and $10^3$ Hz, which is the inertial sub-range (Counihan, 1975). And the power spectral density of the simulated ABL follows a -5/3 slope in the inertial subrange, which satisfies the Kolmogorov’s -5/3 Law. When compared with the Von Kármán and the Kaimal power spectrum in Figure 4.29 (d), the power spectrum of the simulated ABL is agreeable with those empirical formulas.

(a) Dimensionless vertical profile of mean streamwise wind velocity (X=500 mm, Y=0 mm)
(b) Vertical profile of turbulence intensity $I_u$ (X=500 mm, Y=0 mm)

(c) Vertical profile of integral length scale $L_{u}^{x}$ (X=500 mm, Y=0 mm)
According to the vertical profiles of the dimensionless mean streamwise wind velocity,
turbulence intensity and integral length scale, as well as the power spectrum, the flow characteristics generated by Case 5S7-10R6CS2 are considered satisfactory for simulating atmospheric boundary layer associated with terrain type “A” by using 5 modified spires combined with 120 double-height roughness elements (10 rows, 6 columns, double-height roughness elements, staggered). The details and the layout of this set up is given in Table 4.14 and Figure 4.30, respectively.

Table 4.14 Details of the final setup for the simulation of terrain type “A” through 5 spires combined with roughness elements.

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Spire</th>
<th>Roughness element</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>$b_{board}$ (cm)</td>
</tr>
<tr>
<td>5S7-10R6CS2</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure 4.30 Details of the layout for the simulation of terrain type “A” (Case 5S7-10R6CS2)

4.3.2 Simulation ABL in terrain type “B”

Terrain type “B” stands for suburb terrain situation, which is also one of the most common terrain types. The power-law exponent $\alpha$ of it is 0.22 (ASCE 7-16). The
simulation of ABL in terrain type “B” is presented either 3 spires or 5 spires combined with roughness elements.

4.3.2.1 Three spires combined with roughness elements

Based on the experiences of ABL simulations in terrain type “A” using 3 modified spires combined with roughness elements, 3 modified spires with 9 cm wide rectangular board are used to simulate the atmospheric boundary layer in the following tests. In order to study the effect of the number of the single-height roughness elements, three cases have been tested by utilizing 3 modified spires combined with single-height roughness elements, and the details of these cases are shown in Table 4.15.

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Spire Number</th>
<th>(b_{board}) (cm)</th>
<th>Total number</th>
<th>Array (Row × Column)</th>
<th>Influence area ((mm^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>3S9-13R12CA1</td>
<td>3</td>
<td>9</td>
<td>156</td>
<td>13 × 12</td>
<td>550 × 150</td>
</tr>
<tr>
<td>3S9-10R12CA1</td>
<td>3</td>
<td>9</td>
<td>120</td>
<td>10 × 12</td>
<td>720 × 150</td>
</tr>
<tr>
<td>3S9-8R12CA1</td>
<td>3</td>
<td>9</td>
<td>96</td>
<td>8 × 12</td>
<td>900 × 150</td>
</tr>
</tbody>
</table>

Figure 4.31 (a) shows the vertical profile of the dimensionless mean streamwise wind velocity of Cases 3S9-13R12CA1, 3S9-10R12CA1 and 3S9-8R12CA1, and the power-law profile of the target terrain type “B” with \(\alpha=0.22\). After applying curve fitting to these three sets of mean streamwise wind speed profiles, the power-law exponent \(\alpha\) are 0.25, 0.24 and 0.224, respectively. The exponent of Case 3S9-8R12CA1 is more agreeable with the
requirement of terrain type “B”. It can be seen from Figure 4.31 (a), all the raw data in Case 3S9-8R12CA1 match well with the power-law curve of $\alpha = 0.22$.

Figure 4.31 (b) depicts the vertical profile of the turbulence intensity $I_u$. The Walshe’s empirical formula is used to evaluate the turbulence intensity of the generated ABL. The Walshe’s empirical formula profiles of both $\alpha = 0.16$ and $0.28$ are shown, since there is no value of $K$ corresponding to the power-law exponent of terrain type “B” in Table 2.4 (Walshe, 1973). The empirical formula profile for $\alpha = 0.22$ should fall in the zone between these two profiles. The turbulence intensity obtained in these three cases agree well with each other once above the height of $Z=400$ mm. The reason should be that the width of the rectangular board at the top of the modified spires is the same for all three cases. Below the height of 400 mm, the difference of the turbulence intensity among three cases decreases along the increasing height. The turbulence intensity of these three cases are considerably less than that predicted by the Walshe empirical formula when the height is above 250 mm form the tunnel floor. The insufficient turbulence intensity at the top of the simulated ABL is the common challenge if the passive simulation devices are used.
Figure 4.31 Effect of the number of single-height Roughness elements on the flow characteristics (Cases 3S9-13R12CA1, 3S9-10R12CA1 and 3S9-8R12CA1)

(a) Vertical profile of dimensionless mean streamwise wind velocity

(b) Vertical profile of turbulence intensity $I_u$
Based on the results of Figure 4.31, the simulated atmospheric boundary layer of Case 3S9-8R12CA1 shows better results to satisfy the requirement of terrain type “B” from the perspective of vertical profiles of dimensionless mean wind velocity and turbulence intensity. The relative flow characteristics of this case are presented in Figure 4.32.

Figure 4.32 (a) shows the vertical profile of the dimensionless mean streamwise wind velocity of Case 3S9-8R12CA1 and the power-law profile of the target terrain type “B”. The generated boundary layer thickness is found to be 955 mm and the power-law exponent $\alpha$ is 0.224, which satisfies the requirement of the terrain type “B” with $\alpha=0.22$. From Figure 4.32 (a), all the data points agree with the target power-law velocity profile well.

Figure 4.32 (b) depicts the vertical profile of the turbulence intensity $I_u$ and Walshe’s empirical formula corresponding to $\alpha=0.16$ and 0.28. In general, the trend of the simulated turbulence intensity vertical profile is similar to the profiles predicted by Walshe (1973). However, even a rectangular board with a width of 9 cm has been added to the top of the spire, the turbulence intensity at the top part of the generated boundary layer is still less than that predicted by the Walshe’s empirical formula. For the height below 250 mm, the raw data points are within the range between Walshe’s empirical formula of $\alpha=0.16$ and 0.28. Since the simulation devices used in this study are the passive type, the inadequacy of the turbulence intensity at the middle and the upper part is still the common challenge.

From the perspective of Model Law, 955 mm in model scale stands for 360 m in full scale, which means the model scale is about 1:380. So a height of 120 m in full scale would stand
for 310 mm in model scale. Clearly, the turbulence intensity within this range satisfies the requirement of terrain type “B”.

Figure 4.32 (c) gives the vertical profile of the integral length scale. For most of the measurement locations above the height of 350 mm, the integral length scale obtained in Case 3S9-8R12CA1 are less than those by Cook’s empirical formula for terrain type “B”. Based on the model scale of 1:380, the measurement locations below the height of 310 mm in model scale, which stands for 120 m in full scale, all the raw data points are within the range between the ±25% of the citation for Cook’s empirical formula for α=0.22.

Figure 4.32 (d) and (e) depict the power spectrum of the generated atmospheric boundary layer in the log-log coordinates and the Monin coordinates, respectively. The measurement location at X=500 mm, Y=0 mm and Z= 805 mm is selected as the sample location as Section 4.3.1.1. Figure 4.32 (d) shows the inertial sub-range is within the frequency range of $10^2$ and $10^3$ Hz because of the turbulent energy dissipation (Counihan, 1975). It can be observed that in the inertial subrange, the $-5/3$ Kolmogorov’s Law is satisfied. When compared with the Von Kármán and the Kaimal power spectrum density function in Figure 4.32 (e), the simulated power spectrum is agreeable with them.
(a) Vertical profile of dimensionless mean streamwise wind velocity (X=500 mm, Y=0 mm)

(b) Vertical profile of turbulence intensity $I_u$ (X=500 mm, Y=0 mm)
(c) Vertical profile of integral length scale $L_u^k$ (X=500 mm, Y=0 mm)

(d) Power spectrum in log-log coordinates (X=500 mm, Y=0 mm, Z=805 mm)
Based on the results of the vertical profiles of the dimensionless mean streamwise wind velocity, turbulence intensity and integral length scale, as well as the power spectrum given in Figure 4.32, the flow characteristics generated by the Case 3S9-8R12CA1 can satisfy the requirement of simulated atmospheric boundary layer associated with terrain type “B”. The details and the layout of the set up is given in Table 4.16 and Figure 4.33, respectively.
Table 4.16 Details of the final setup for the simulation of terrain type “B” through 3 spires combined with roughness elements.

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Spire Number</th>
<th>(b_{board}) (cm)</th>
<th>Total number</th>
<th>Type</th>
<th>Array Row × Column</th>
<th>Influence area</th>
</tr>
</thead>
<tbody>
<tr>
<td>3S9-8R12CA1</td>
<td>3</td>
<td>9</td>
<td>96</td>
<td>Single</td>
<td>8 × 12</td>
<td>900×150</td>
</tr>
</tbody>
</table>

Figure 4.33 Details of the layout for the simulation of terrain type “B” (Case 3S9-8R12CA1)

4.3.2.2 Five spires combined with roughness elements

The atmospheric boundary layer associated with terrain type “B” was also simulated by using 5 spires combined with roughness elements. Based on the simulation results in Section 4.3.1.2, 5 modified spires with 7 cm rectangular board are used to simulate the atmospheric boundary layer in the following tests. Three cases have been tested to study the effect of roughness element number by utilizing 5 modified spires combined with single-height roughness elements, and the details of these cases are given in Table 4.17.
Table 4.17 Details of the cases to study the effect of the roughness element number

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Case ID</th>
<th>Spire Number</th>
<th>$b_{board}$ (cm)</th>
<th>Roughness element number</th>
<th>Array (Row × Column)</th>
<th>Influence area ($mm^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4B</td>
<td>5S7-5R10CA1</td>
<td>5</td>
<td>7</td>
<td>50</td>
<td>5 × 10</td>
<td>1440 × 180</td>
</tr>
<tr>
<td>5B</td>
<td>5S7-10R10CA1</td>
<td>5</td>
<td>7</td>
<td>100</td>
<td>10 × 10</td>
<td>720 × 180</td>
</tr>
<tr>
<td>6B</td>
<td>5S7-20R10CA1</td>
<td>5</td>
<td>7</td>
<td>200</td>
<td>20 × 10</td>
<td>360 × 180</td>
</tr>
</tbody>
</table>

Figure 4.34 (a) depicts the vertical profile of the dimensionless mean streamwise wind velocity of Cases 5S7-5R10CA1, 5S7-10R10CA1 and 5S7-20R10CA1, and the power-law profile of the target terrain type “B” with $\alpha=0.22$. The power-law exponent $\alpha$ of these three cases are 0.23, 0.27 and 0.29, respectively. It can be seen from Figure 4.34 (a) that all the raw data points of the dimensionless mean streamwise wind velocity profile obtained in Cases 5S7-10R10CA1 and 5S7-20R10CA1 are less than that of the power-law curve corresponding to terrain type “B” below the dimensionless height of 0.4, whereas that obtained in Case 5S7-5R10CA1 shows an excellent agreement with the target power-law curve of the terrain type “B”.

Figure 4.34 (b) illustrates the vertical profiles of the turbulence intensity $I_u$ for the three studied cases. The turbulence intensity obtained in these three cases are compared with the Walshe’s empirical formula corresponding to $\alpha = 0.16$ and 0.28. The turbulence intensity obtained in these three cases agrees well with each other above the height of $Z=400$ mm, since the rectangular board at the top of the modified spires has the same width for these three cases. And for the height above 300 mm above the tunnel floor, the
turbulence intensity for all cases are considerably less than that predicted by the Walshe empirical formula, which is the common challenge of passive simulation devices. Below the height of 400 mm, the difference of the turbulence intensity among these three cases decreases along the increasing height.

(a) Vertical profile of dimensionless mean streamwise wind velocity
Based on the results of Figure 4.34, the vertical profiles of the dimensionless mean streamwise velocity of the generated ABL by Case 5S7-5R10CA1 yields the best result among all, and the relative flow characteristics of Case 5S7-5R10CA1 are presented in Figure 4.35.

Figure 4.35 (a) shows the dimensionless vertical profile of mean streamwise wind velocity and the power-law profile of the target terrain type “B”. After applying curve fitting to the profile of mean streamwise wind velocity, the power-law exponent $\alpha$ is 0.22 and the generated boundary layer thickness is 705 mm, which satisfies the requirement of the terrain type “B” with $\alpha=0.22$. 

(b) Vertical profile of turbulence intensity $I_u$

Figure 4.34 Effect of the number of single-height roughness elements on the flow characteristics (Cases 3S9-13R12CA1, 3S9-10R12CA1 and 3S9-8R12CA1)
Figure 4.35 (b) depicts the vertical profile of the turbulence intensity $I_u$ and the profiles of Walshe’s empirical formula corresponding to $\alpha=0.16$ and 0.28. A good agreement is observed between the trend of the vertical profile of the turbulence intensity and the profiles predicted by Walshe (1973). The value of the turbulence intensity doesn’t change a lot once above the height of 350 mm, because the width of added rectangular board of the spires is same.

Figure 4.35 (c) gives the vertical profile of the integral length scale. Within the generated boundary layer, the integral length scale obtained in Case 3S9-8R12CA1 are more or less within the range between $\pm 25\%$ of the Cook’s empirical formula for $\alpha=0.22$.

Figure 4.35 (d) and (e) depict the power spectrum of the generated atmospheric boundary layer in the log-log coordinates and the Monin coordinates, respectively. The sample location is also selected to be at $X=500$ mm, $Y=0$ mm and $Z=355$ mm as Section 4.3.1.2. Figure 4.35 (d) shows that the turbulent energy dissipates in the inertial sub-range, which is within the frequency range of $10^2$ and $10^3$ Hz (1971, Counihan). The Kolmogorov’s -5/3 Law can be observed in the intermediate range, where the curve of the power spectral density follows a -5/3 slope. When compared with the Von Kármán spectrum and the Kaimal power spectrum density function in Figure 4.35 (e), it is clear that the simulated power spectrum is agreeable with them.
(a) Vertical profile of dimensionless mean streamwise wind velocity (X=500 mm, Y=0 mm)

(b) Vertical profile of turbulence intensity $I_u$ (X=500 mm, Y=0 mm)
(c) Vertical profile of integral length scale $L_u^x$ (X=500 mm, Y=0 mm)

(d) Power spectrum in log-log coordinates (X=500 mm, Y=0 mm, Z=355 mm)
Figure 4.35 Flow characteristics of atmospheric boundary layer simulation for terrain type “B” through 3 spires combine with roughness elements.

Based on the analysis about the vertical profiles of the dimensionless mean streamwise wind velocity, turbulence intensity and integral length scale, as well as the power spectrum, the flow characteristics generated by the Case 5S7-5R10CA1 can meet the simulation requirement of atmospheric boundary layer associated with terrain type “B”. The details and the layout of this case are given in Table 4.18 and Figure 4.36, respectively.

Table 4.18 Details of the final setup for the simulation of terrain type “A” through 5 modified spires combined with single-height roughness elements.

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Spire</th>
<th>Roughness element</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>b_{board} (cm)</td>
</tr>
<tr>
<td></td>
<td>Total number</td>
<td>Array (Row × Column)</td>
</tr>
<tr>
<td>5S7-5R10CA1</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>
Figure 4.36 Details of the layout for the simulation of terrain type “B” (Case 5S7-5R10CA1)
5. CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

In the current study, atmospheric boundary layers of terrain types “A” and “B” have been simulated in an open-loop wind tunnel using the spire-roughness-element technique. The flow quality at the test section of the empty wind tunnel is evaluated first, which includes the relation between the fan motor frequency and the generated wind speed, and the symmetry and uniformity of the flow field at the test section. Two sets of spires, with a total number of 3 or 5, have been designed and manufactured according to Irwin’s approach. And the roughness element has been designed based on the experiences of previous researchers (Sill, 1988; Gartshore and Croos, 1995; Xu, 2007) and manufactured as well. Then, the independent effect of spires and roughness elements on the flow characteristics of the generated ABL have been examined separately. In order to improve the generated flow characteristics, the idea of using modified spire and double-height roughness elements were proposed and the effects of them have been studied as well. At the end, the atmospheric boundary layer of terrain types “A” and “B” have been simulated in the open-loop wind tunnel using 3 or 5 spires combined with roughness elements, respectively.

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

1. The flow properties at the test section of the empty wind tunnel are evaluated. The wind velocity has a linear relationship with the motor frequency and the proportional coefficient is 0.25. The flow field at the test section of the empty wind
tunnel has good symmetry and uniformity in both vertical and horizontal directions.

2. Design and manufacture the spires followed the Irwin’s approach and the thickness of the generated atmospheric boundary layer by 3-spire and 5-spire are 955 mm and 605 mm, respectively, which agree with the boundary layer thickness predicted by the Irwin’s approach.

3. The roughness element can be used to retard the bottom part of the mean wind velocity profile. The height can be influenced by the roughness elements is up to 400 mm, which is about 6.5 times of the roughness element height.

4. The effect of the modified spires and double-height roughness element have been examined. The modified spires with rectangular board can be used to improve the turbulence intensity in the upper part of the generated boundary layer, whereas the double-height roughness elements can increase the turbulence intensity at the middle part of the generated boundary layer.

5. The terrain types “A” and “B” are simulated successfully by the 3 or 5 modified spires combined with roughness elements in the open-loop wind tunnel. The flow characteristics of the generated boundary layer are satisfactory for the wind engineering application.

5.2 Future work

In order to meet the requirement of wind engineering applications in the open-loop
wind tunnel, more experimental studies need to be calculated. Some future works are suggested as followed.

1. To meet all terrain condition categories corresponding to the ASCE exposure type (ASCE, 2016), the atmospheric boundary layers associated with terrain type “C” and “D” should be simulated by the passive devices, which requires new designing of spires.

2. Since the common issue of using passive devices is the inadequacy of the generated turbulence intensity, more studies need to be carried out in the wind tunnel for increasing the turbulence intensity, especially for the upper part of the generated boundary layer.
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Appendix A: UNCERTAINTY ANALYSIS

The uncertainty in the mean wind velocity measurement through hot-wire anemometer mainly comes from the process of calibrating the hot-wire anemometer and the process of calculating the turbulence parameters. In this appendix, the uncertainty in the time averaged flow velocity $\bar{U}$, the turbulence intensity $I_u$, and the integral length scale $L_u$ will be shown.

The very first step to estimate the uncertainty of mean wind velocity measurement through the hot-wire anemometer is to analyze the uncertainty of the instantaneous velocity $U_i$, because the uncertainties in the above parameters were estimated based on the uncertainty in the instantaneous velocity $U_i$.

A.1 Uncertainty of the calibration

The calibration uncertainty mainly comes from two parts, the uncertainty from the polynomial curve fitting which give the coefficient values used for calibration equation $U = C_0 + C_1E + C_2E^2 + C_3E^3 + C_4E^4 + C_5E^5$ and the uncertainty in the velocity $U_{pito}$ measured by the pitot tube.

The relative velocity uncertainty $\Delta U_{pito}$ measured by Pitot-static tube was less than 2.0% (Dwyer, 2015). The relative velocity uncertainty $\Delta U_{fit}$ because of the curve fitting error is around 0.5% (Beyer, 1976). Thus, the total relative velocity uncertainty due to the calibrations are:
\[
\Delta U = \sqrt{(\Delta U_{\text{pitot}})^2 + (\Delta U_{\text{fit}})^2} \approx 2.06% \tag{A.1}
\]

**A.2 Uncertainty of calculating the turbulence parameters**

The uncertainty analysis results of mean wind velocity, turbulence intensity and integral length scale are shown in Table A.1. All the turbulence parameters are calculated for 6, 7.5, 9, 10.5, 12, 13.5 and 15 m/s, respectively. And the calculation approaches are shown in the following part.

<table>
<thead>
<tr>
<th>Velocity</th>
<th>6</th>
<th>7.5</th>
<th>9</th>
<th>10.5</th>
<th>12</th>
<th>13.5</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta \bar{U} / \bar{U})</td>
<td>4.2%</td>
<td>3.7%</td>
<td>2.7%</td>
<td>1.9%</td>
<td>1.1%</td>
<td>0.8%</td>
<td>0.6%</td>
</tr>
<tr>
<td>(\Delta I_u / I_u)</td>
<td>6.2%</td>
<td>4.1%</td>
<td>3.6%</td>
<td>2.4%</td>
<td>1.7%</td>
<td>1.3%</td>
<td>0.8%</td>
</tr>
<tr>
<td>(\Delta L_u^x / L_u^x)</td>
<td>8.7%</td>
<td>7.2%</td>
<td>6.6%</td>
<td>4.1%</td>
<td>2.9%</td>
<td>1.1%</td>
<td>1.1%</td>
</tr>
</tbody>
</table>

1) The mean wind velocity \(\bar{U}\) is calculated as:

\[
\bar{U} = \frac{1}{N} \sum_{i=1}^{N} U_i \tag{A.2}
\]

Thus, the uncertainty of mean wind velocity is estimated as:

\[
\Delta \bar{U} = \sqrt{\sum_{i=1}^{N} \left( \frac{\partial \bar{U}}{\partial U_i} \Delta U_i \right)^2} = \frac{1}{N} \sqrt{\sum_{i=1}^{N} \left( \Delta U_i \right)^2} \tag{A.3}
\]

Based on the second row of the Table A.1, the average uncertainty of mean wind velocity is 1.94%.

2) The turbulence intensity \(I_u\) is calculated based on Eq. (2.5) as:
\[ I_u = \frac{U_{rms}}{\bar{U}} \times 100 \]  \hspace{1cm} (A.4)

of which the uncertainty is estimated by:

\[ \frac{\Delta I_u}{I_u} = \sqrt{\left(\frac{\Delta \bar{U}}{\bar{U}}\right)^2 + \left(\frac{\Delta u_{rms}}{u_{rms}}\right)^2} \]  \hspace{1cm} (A.5)

where \( U_{rms} \) is root mean square velocity.

According to the third row of the Table A.1, the average uncertainty of turbulence intensity is 2.87%.

3) The integral length scale \( L_u^x \) is calculated based on Eqs. (2.12) and (2.13), and uncertainty of which is estimated by:

\[ \frac{\Delta L_u^x}{L_u^x} = \sqrt{\left(\frac{\Delta \bar{U}}{\bar{U}}\right)^2 + \left(\frac{\Delta \tau}{\tau}\right)^2} \]  \hspace{1cm} (A.8)

and

\[ \frac{\Delta \tau}{\tau} = \sqrt{\left(\frac{\Delta \rho_u(\Delta t)}{\rho_u(\Delta t)}\right)^2} \]  \hspace{1cm} (A.9)

where \( \rho_u \) is the autocorrelation factor and \( \Delta t \) is the time interval between consecutive samples.

From Table A.1, the average uncertainty of integral length scale is 4.52%.
Appendix B: CALIBRATION OF A HOT-WIRE PROBE

B.1 Main procedures of performing calibration

a. Since the hot-wire probe is very sensitive to the variation of environment conditions, many parameters associated with the current air properties need to be measured before the calibration, such as the wet temperature, the dry temperature and the ambient pressure in the lab.

b. The Labview code (Hotwire Calibration) of the calibration system is shown in Figure B.1. Filling in the values of the measured wet temperature, dry temperature and ambient pressure in the form and click the “Initial” button, the current air density and humidity can be calculated by the Labview code and shown on the screen.

c. The sampling frequency (rate) and the sampling time are determined based on the requirement of specific tests. Once determined, the sampling number can be computed as the product of these two parameters. Fill in the sampling rate and sampling number at the corresponding location of the user interface.

d. Adjust the pressure regulator and then record the corresponding voltage outputs E from hot-wire probe and the mean wind velocity U from the pitot tube.

e. Repeat step d to get 11 pairs of voltage outputs E and the mean wind velocity U.
f. Using the voltage and velocity data in pairs of No. 1, 3, 5, 7, 9, 11 to determine the calibration coefficients $C_0$ to $C_5$ using the Matlab code.

g. To check the accuracy of the calibration coefficients determined in Step f, use the remaining 5 pairs of voltage and wind velocity data as a check. Apply the calibration coefficients to a particular voltage value to find the corresponding wind velocity, then compare it with the one measured by the pitot static tube. If the error is less than 1\%, then the calibration is considered as satisfactory.
B.2 Matlab code for calibration

clear;
[NUM]=xlsread('18_05_2017_Calibration_wind tunnel','A18:C28'); % read the data from excel
U=[NUM(:,2)];
E=[NUM(:,3)];
% Calculating the 6 calibration coefficients
U_cal=downsample(U,2);
E_cal=downsample(E,2)';
i=0;
x1=ones(1,6);
x3=E_cal.^2;
x4=E_cal.^3;
x5=E_cal.^4;
x6=E_cal.^5;
A1=[x1;E_cal;x3;x4;x5;x6]';
C1=A1\U_cal;
C1=C1';
y1=ones(1,11)';
y3=E.^2;
y4=E.^3;
y5=E.^4;
y6=E.^5;
E1=[y1';E;y3;y4';y5';y6'];
U1_estimate=C1*E1;
U1_est=U1_estimate';
ErrorPer_1=(U-U1_est)/U;  % Calculating the error percentage
ErrorPer_1=ErrorPer_1(:,11);
% Calculating the 5 calibration coefficients
E_cal_2=E_cal(:,1:5);
U_cal_2=U_cal(1:5,:);
x1=ones(1,5);
x3=E_cal_2.^2;
x4=E_cal_2.^3;
x5=E_cal_2.^4;
A2=[x1;E_cal_2;x3;x4;x5;]';
C2=A2\U_cal_2;
C2=C2';
y1=ones(1,11)';
y3=E.^2;
y4=E.^3;
y5=E.^4;
E2=[y1';E';y3';y4';y5'];
U2_estimate=C2*E2;
U2_est=U2_estimate';
ErrorPer_2=(U-U2_est)/U;    % Calculating the error percentage
ErrorPer_2=ErrorPer_2(:,11);
C1=C1';
C2=C2';
Result=[NUM,100*ErrorPer_1,100*ErrorPer_2];
% Output the results to the excel
s1=xlswrite('calibrationresults',[Result,'A3:E13']);
s2=xlswrite('calibrationresults',[C1,'A17:A22']);
s3=xlswrite('calibrationresults',[C2,'C17:C21']);
Appendix C: MATLAB PROGRAM

C.1 Matlab code for processing the raw voltage data from Hot-wire anemometer

% MATLAB file for processing the measurement data obtained from Hot-wire Anemometer.

clear;clc;  % Initialising
load points;  % Load the data

% Enter the height of the measurement locations
H=[5;55;105;205;305;455;605;755;905;1005];

% Arrange the data as the order of the measurement locations
rawdata(:,1)=PointHot_wire.Data;
rawdata(:,2)=Point1Hot_wire.Data;
rawdata(:,3)=Point2Hot_wire.Data;
rawdata(:,4)=Point3Hot_wire.Data;
rawdata(:,5)=Point4Hot_wire.Data;
rawdata(:,6)=Point5Hot_wire.Data;
rawdata(:,7)=Point6Hot_wire.Data;
rawdata(:,8)=Point7Hot_wire.Data;
rawdata(:,9)=Point8Hot_wire.Data;
rawdata(:,10)=Point9Hot_wire.Data;

% Read the number of the points
k=size(rawdata);
data_number=k(1,2);

% Use function to calculate the mean wind speed and turbulence intensity
for i=1:data_number
    [T_mean(i), T_std(i),data(:,i)] = myfunc(rawdata(:,i))
end
U=T_mean;
TB=T_std./T_mean;
TB=100*TB;

% Judge the ABL thickness
for n=1:data_number-3
    error1=abs((U(n+1,1)-U(n,1))/U(n,1));
    error2=abs((U(n+2,1)-U(n+1,1))/U(n+1,1));
    error3=abs((U(n+3,1)-U(n+2,1))/U(n+2,1));
    if error1<=0.01&&error2<=0.01&&error3<=0.01
        r=n+1;
        break;
    end
end

h=H(1,r);  % h is the ABL thickness
model_scale_factor=450/h;    % Calculate the model scale

% Nomalization of the height and velocity
ave_U=sum(U(r:N))/(N+1-r);
DimenlessVY0=U./ave_U;
DimenlessHY0=H./H(r);

% Power-law curve fitting
myfittype=fittype('x^a','dependent',{'y'},'independent',{'x'},'coefficients',{'a'});
myfit=fit(DimenlessHY0(1:end),DimenlessVY0(1:end),myfittype);
C=confint(myfit,0.90);
a=sum(C)/2;    % a is the alpha value of power-law;

% Vertical profile of dimensionless mean streamwise wind velocity
figure(1)
title('Wind Velocity Profile','FontSize',14);
hold on;
x=linspace(0,1,2000);
y=x.^0.22;  % Power-law curve for a=0.22
plot(y,x,'b');
scatter(DimenlessVY0(1:r),DimenlessHY0(1:r),'r*');
legend('Power law (alpha is 0.22)','raw data','Location','Best','FontSize',13);
xlabel('Dimensionless wind speed (U/U_\delta)','FontSize',13);
ylabel('Dimensionless height (Z/\delta)','FontSize',13);
axis([0 1.2 0 1.2]);
grid on;
hold off;
print(1,'-dpng','Y=0 Dimensionless Wind Velocity Profile');
Calculate the turbulence intensity

\begin{verbatim}
figure(2)
set(gca,'Fontname','Times New Roman','FontSize',20);
plot(TB(1:end),H(1:end),'b*','markers',10);
hold on;
xlabel('Turbulence Intensity (%)','FontSize',20);
ylabel('Height(m)','FontSize',20);
grid on;
z=linspace(0,1100,2000);  % Profile of the Walshe's empirical formula.
IU1=258*(0.005^0.5)*((10./z).^0.16);
plot(IU1,z/model_scale_factor);
axis([0 30 0 1200])
IU2=258*(0.015^0.5)*((10./z).^0.28);
plot(IU2,z/model_scale_factor);
legend('raw data','Walshe, K=0.005','Walshe, K=0.015','Location','NorthEast');
hold off;
print(2,'-dpng','Y=0 Turbulence Intensity');
\end{verbatim}

Calculate the integral length scale

\begin{verbatim}
fre=32768;km=200000;
for m=1:data_number
    myacf(:,m)=autocorr(data(:,m),km);
    for i=1:km
        if myacf(i,m)<=0;
            p(m)=i;
            break;
        elseif i==km
            p(m)=i;
            break;
        end
    end
    result(m)=sum(myacf(1:p(m),m))/fre;
end
ILS=result'*T_mean;
\end{verbatim}

Vertical profile of Integral length scale

\begin{verbatim}
figure(3)
set(gca,'Fontname','Times New Roman','FontSize',20);
\end{verbatim}
plot(ILS(1:end),H(1:end),'b*','markers',10);
hold on
z01=0.25; % Profile of the Cook's empirical formula.
z_d=linspace(0,500,2000);
y1=25*(z_d).^0.35*z01^(-0.063)*model_scale_factor/1000;
plot(1/497*y1,model_scale_factor*z_d,'r');
axis([0 1.4 0 1200]);
xlabel('Integral length scale(m)','FontSize',20);
ylabel('Height z,(mm)','FontSize',20);
legend('Y=0','Cook z=0.25','Location','NorthEast','FontSize',16);
grid on;
hold off;
print(3,'-dpng','Y=0 Integral length scale');

% Calculate the Power spectrum density
PSDn=1:2049;PSDf=1:2049; % Initialising
PSDf=PSDf';nfft=32768; % Initialising
i=13;
window=boxcar(length(data(:,i)));
[Pxx,PSDf]=periodogram(data13,window,nfft);
RN=Pxx.*PSDf./T_std(i)^2;
PSDf=PSDn*ILS(i)/T_mean(i);
vonkarmanRN=4*PSDf./(1+70.8*PSDf.^2).^(5/6); % Von Karman empirical formula
kaimalRN=2/3*50*PSDf./(1+50*PSDf).^(5/3); % Kaimal spectrum

% Power spectrum profile
figure(4)
set(gca,'Fontname','Times New Roman','FontSize',20);
loglog(PSDf(1:2049),abs(RN(1:2049)));
hold on
loglog(PSDf(1:2049),vonkarmanRN(1:2049));
loglog(PSDf(1:2049),kaimalRN(1:2049))
legend('raw data','Von Karman','Kaimal','Location','NorthEast');
grid on
title('Power Spectrum Density','FontSize',16);
xlabel('n*Lz/U','FontSize',20);
ylabel('Magnitude [(m/s)^2/Hz]','FontSize',20);
hold off
print(4,'-dpng','Y=0 Power Spectrum Density');
C.2 Attached function code for applying calibration coefficients to convert the raw voltage data to corresponding velocity data

```matlab
function [T_mean, T_std, data] = myfunc(rawdata)

K=[5670.521199;-11838.61525;9273.096441;-3233.659875;424.5264188;0;];  
% Enter the calibration coefficients
[length1, width1] = size(rawdata);
I = ones(length1, 1);
data = K(1)*I + K(2)*rawdata + K(3)*(rawdata.^2) + K(4)*(rawdata.^3) + K(5)*(rawdata.^4) + K(6)*(rawdata.^5);  
% Use the formula to get the velocity through rawdata(voltage)
T_std = std(data);
T_mean = mean(data);
end
```
## Appendix D: LIST OF ALL TESTING CASES

### D.1 List of all cases using three spires

<table>
<thead>
<tr>
<th>Spire</th>
<th>Roughness element</th>
<th>Case ID</th>
<th>No.</th>
<th>$b_{board}$ (cm)</th>
<th>No.</th>
<th>Type</th>
<th>Array type</th>
<th>Influence area ($mm^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3S0</td>
<td></td>
<td>3S0-20R10CA1</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3S0-40R10CA1</td>
<td>3</td>
<td>0</td>
<td>400</td>
<td>Single</td>
<td>20 × 10</td>
<td>180 × 180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3S9-40R10CA1</td>
<td>3</td>
<td>9</td>
<td>400</td>
<td>Single</td>
<td>40 × 10</td>
<td>180 × 180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3S12.5-40R10CA1</td>
<td>3</td>
<td>12.5</td>
<td>400</td>
<td>Single</td>
<td>40 × 10</td>
<td>180 × 180</td>
</tr>
<tr>
<td>3S12.5</td>
<td></td>
<td>3S12.5-20R10CA2</td>
<td>3</td>
<td>12.5</td>
<td>400</td>
<td>Double</td>
<td>20 × 10</td>
<td>360 × 180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3S12.5-12R10CS2</td>
<td>3</td>
<td>12.5</td>
<td>240</td>
<td>Double</td>
<td>12 × 10</td>
<td>600 × 180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3S12.5-11R10CS2</td>
<td>3</td>
<td>12.5</td>
<td>220</td>
<td>Double</td>
<td>11 × 10</td>
<td>650 × 180</td>
</tr>
<tr>
<td>3S9</td>
<td></td>
<td>3S9-13R12CA1</td>
<td>3</td>
<td>9</td>
<td>156</td>
<td>Single</td>
<td>13 × 12</td>
<td>550 × 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3S9-10R12CA1</td>
<td>3</td>
<td>9</td>
<td>120</td>
<td>Single</td>
<td>10 × 12</td>
<td>720 × 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3S9-8R12CA1</td>
<td>3</td>
<td>9</td>
<td>96</td>
<td>Single</td>
<td>8 × 12</td>
<td>900 × 150</td>
</tr>
</tbody>
</table>

### D.2 List of all cases using five spires

<table>
<thead>
<tr>
<th>Spire</th>
<th>Roughness element</th>
<th>Case ID</th>
<th>No.</th>
<th>$b_{board}$ (cm)</th>
<th>No.</th>
<th>Type</th>
<th>Array type</th>
<th>Influence area ($mm^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5S0</td>
<td></td>
<td>5S0-30R10CA1</td>
<td>5</td>
<td>0</td>
<td>300</td>
<td>Single</td>
<td>30 × 10</td>
<td>240 × 180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5S7-40R10CA1</td>
<td>5</td>
<td>7</td>
<td>400</td>
<td>Single</td>
<td>40 × 10</td>
<td>180 × 180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5S7-20R10CA2</td>
<td>5</td>
<td>7</td>
<td>400</td>
<td>Double</td>
<td>20 × 10</td>
<td>360 × 180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5S7-10R10CA2</td>
<td>5</td>
<td>7</td>
<td>200</td>
<td>Double</td>
<td>10 × 10</td>
<td>720 × 180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5S7-10R6CS2</td>
<td>5</td>
<td>7</td>
<td>120</td>
<td>Double</td>
<td>10 × 6</td>
<td>720 × 300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5S7-5R10CA1</td>
<td>5</td>
<td>7</td>
<td>50</td>
<td>Single</td>
<td>5 × 10</td>
<td>1440 × 180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5S7-10R10CA1</td>
<td>5</td>
<td>7</td>
<td>100</td>
<td>Single</td>
<td>10 × 10</td>
<td>720 × 180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5S7-20R10CA1</td>
<td>5</td>
<td>7</td>
<td>200</td>
<td>Single</td>
<td>20 × 10</td>
<td>360 × 180</td>
</tr>
</tbody>
</table>
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