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Designing small wind turbines for highly turbulent sites

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Abstract

The use of small grid-connected wind turbines in the built environment is increasing. The international wind turbine design standard is based on open terrain sites, but in the built environment, the turbulence intensity is much higher than in open terrain and can lead to premature fatigue of turbines This paper compares the turbulence power spectral densities from direct measurement on the rooftop of Bunning Group Ltd's warehouse at Port Kennedy, Western Australia, with predictions from the von Karman and Kaimal spectra used by turbulence models in the design standard. Both model spectra under estimate the magnitude of the measured values for all wind components although the Kaimal spectra provides more realistic values in terms of predicting the turbulence power spectra of lateral and vertical wind components in the built-environment. A corrected Kaimal model is proposed that has good agreement with measured values and can be viewed as a first step towards upgrading the existing standard with a dedicated design model for the built environment.

Keywords: Small wind turbines, Built environment, Power spectral density, Turbulence models.

1. Introduction

Small wind turbines, defined as having a swept area less than 200 m^2 and traditionally used in off-grid areas, are frequently being used in the built environment and the proportion of systems that are grid-connected is increasing [1]. There have, however, been some notable failures of small wind turbines in the built environment, particularly where turbines were mounted on top of buildings [e.g. 2, 3]. There is some evidence that these kinds of failures are linked to inadequate turbine design for the resource at the site. Many of these complex terrain sites are often characterised by highly turbulent wind flow, and elevated turbulence intensity has been found to be the most important factor in reducing turbine fatigue life [4]. The current IEC international design standards for wind turbines are based on wind turbines in open terrain and do not include specific design models for highly turbulent sites [5]. This implies a need to review the current design models in the standard to improve their suitability for highly turbulent sites [4,6]. Detailed measurements of turbulence over open terrain areas under different conditions of atmospheric stability shows that existing theories describe the flow over these surfaces quite well [7, 8]. Within the built environment, however, less is known of models of atmospheric turbulent spectra. In IEC61400-2, von Karman and Kaimal spectra have been suggested as stochastic turbulence models that can be used for design load calculations but there is no indication within the standard of the accuracy of these models for the built environment [5].

In this research the turbulence power spectral densities of three wind components under neutral atmospheric conditions are measured on the rooftop of Bunning Group Ltd's warehouse at Port Kennedy in Western Australia. Measurements are compared with calculated spectral densities from the von Karman and Kaimal models to assess the suitability of these models to predict the structure of the turbulence at a small wind turbine site in the built environment.

2. Method

2.1 Site Measurements

This study makes use of data, collected from a wind monitoring system on the roof of a large warehouse belonging to the hardware chain Bunnings Ltd. in the suburb of Port Kennedy, Perth, Western Australia. The warehouse is a rectangular building, with its long-axis oriented NNE-SSW, a façade wall around the edge of the roof that is h = 8.5 m a.g.l, and a very low pitched roof (almost flat). The building lies approximately 5km distant from the coast (Indian Ocean) with the prevailing winds from the south-west. The warehouse is situated in a commercial estate but has no larger buildings or large trees in the vicinity.

The wind monitoring system was installed in September 2009 as part of a wind resource assessment for the installation of five small wind turbines that were later commissioned in March 2010 A Gill Wind Master Pro 3D ultrasonic anemometer was installed on a boom on a 5.3 m mast attached to the front-façade of the warehouse (Figure 1). The boom had a sliding collar in order to position the ultrasonic anemometer at different heights above the roof. The data consists of 10-minute averaged records of 10Hz sampled data over a two year period. To reduce processing time, smaller records of 10 days of data were extracted for each of four normalized heights studied; z/h = 1.35, 1.46, 1.58 and 1.70, where z is the height of the anemometer a.g.l. Figure 1 indicates the position of the ultrasonic anemometer on the roof.

Figure1. A photograph of the front view of the Bunnings warehouse showing the five small wind turbines and the ultrasonic anemometer position (red circle)

2.2. Data Analysis

The data series of 10 days' worth of 10-minute averaged records at different heights from the rooftop of the warehouse was analysed to investigate the suitability of the turbulence models from the design standard.

The von Karman and Kaimal turbulence models in the standard both assume neutral atmospheric stability and the first step in processing the data was to filter each component of the raw three-dimensional wind speed measurements (longitudinal, lateral and vertical) using Pasquill stability classes in order to select only wind data recorded under neutral conditions. Based on a table of roughness lengths, surface characteristics and roughness classes from the European wind atlas, the aerodynamic roughness of the Bunnings warehouse area was estimated to be 50 cm [9]. The curves presented by Golder [10] were then used to find the range of Monin-Obukhov lengths corresponding to neutral atmospheric conditions on the roof of the warehouse and these values were then used to filter the raw measurements. The next part of the procedure was to rotate the filtered wind speed data from the reference frame of the ultrasonic anemometer to the reference frame of the mean three-dimensional wind speed and direction, for each 10-minute averaged record

To find the turbulence power spectral density for each 10-minute averaged record, the mean longitudinal, lateral and vertical wind components were separately subtracted from their respective sampled measurements to leave the fluctuations for each component. The autocorrelation of the fluctuations was then computed and a Fast Fourier Transform of this autocorrelation provided the data for the power spectral density plots. The power spectra for different 10-minute averaged records at z/h = 1.35, 1.46, 1.58 and 1.70 in neutral atmospheric conditions for longitudinal, lateral and vertical components were then calculated, averaged over the 10 day period and compared with the von Karman and Kaimal spectra models

3. Results

Figure 2(a-c) shows the average values of turbulence power spectral density, S_k, for longitudinal (k = 1), lateral (k= 2) and vertical (k = 3) wind components plotted against normalized frequency (fz_s'/U, $z_s' = z - z_d$, where z_d is the zero-plane displacement height). Predicted values by the von Karman and Kaimal models are shown for comparison. As is visually apparent from Figure 2a the longitudinal component of the spectra of the measured data is underestimated by both the von Karman and Kaimal models for normalized frequencies larger than 0.1, although the Kaimal model appears closer to the measured values at lower frequencies, particularly at higher heights. For the lateral component of Figure 2b , the models underestimate measured values at normalized frequencies above 0.2 and overall the Kaimal model provides a better prediction. For the vertical component of Figure 2c, the calculated values from the von Karman model are markedly inaccurate whereas the values predicted by the Kaimal model underestimate the observed spectra close to the roof at normalized frequencies larger than 0.3 but further from the rooftop the discrepancy becomes negligible.

A more quantitative evaluation was performed through calculating the Misfit Function L_1 norm [11], which is shown in Table 1.The L1 norm is a measure of how well the model spectra fit to the measured data where the smaller the norm value, the better the fit. Generally the values of the L_1 norm for the Kaimal model are clearly smaller compared to the equivalent values for the von Karman model in terms of lateral and vertical components, especially for the vertical component near to the roof. This suggests the Kaimal spectra may provide more realistic predictions of the turbulence structure of lateral and vertical wind components in the built-environment.. Such a result is hardly surprising as the von Karman model assumes isotropic turbulence and the conditions in the built environment are far from homogeneous. In terms of the turbulence spectra predicted for the longitudinal component, the values of the L_1 norm for both models are generally in agreement and the calculated values for L_1 for both models decreased with increasing distance from the roof. Essentially, with increasing distance from the surface of the roof, the inhomogeneous structures from the underlying surface are averaged out and the turbulence becomes quasi isotropic at least in the horizontal plane.

At high frequencies, whilst the von Karman and Kaimal models as outlined in IEC61400-2 can predict the trend, if not the magnitude, of longitudinal turbulence spectra in the built-environment only the Kaimal model provides a reasonable estimate of the trend of turbulence spectra for the lateral and vertical components. The suggested form of the Kaimal model in IEC61400-2, however, cannot predict the magnitude of the turbulence spectra with a high degree of agreement compared to the real turbulence conditions especially close to building surfaces.

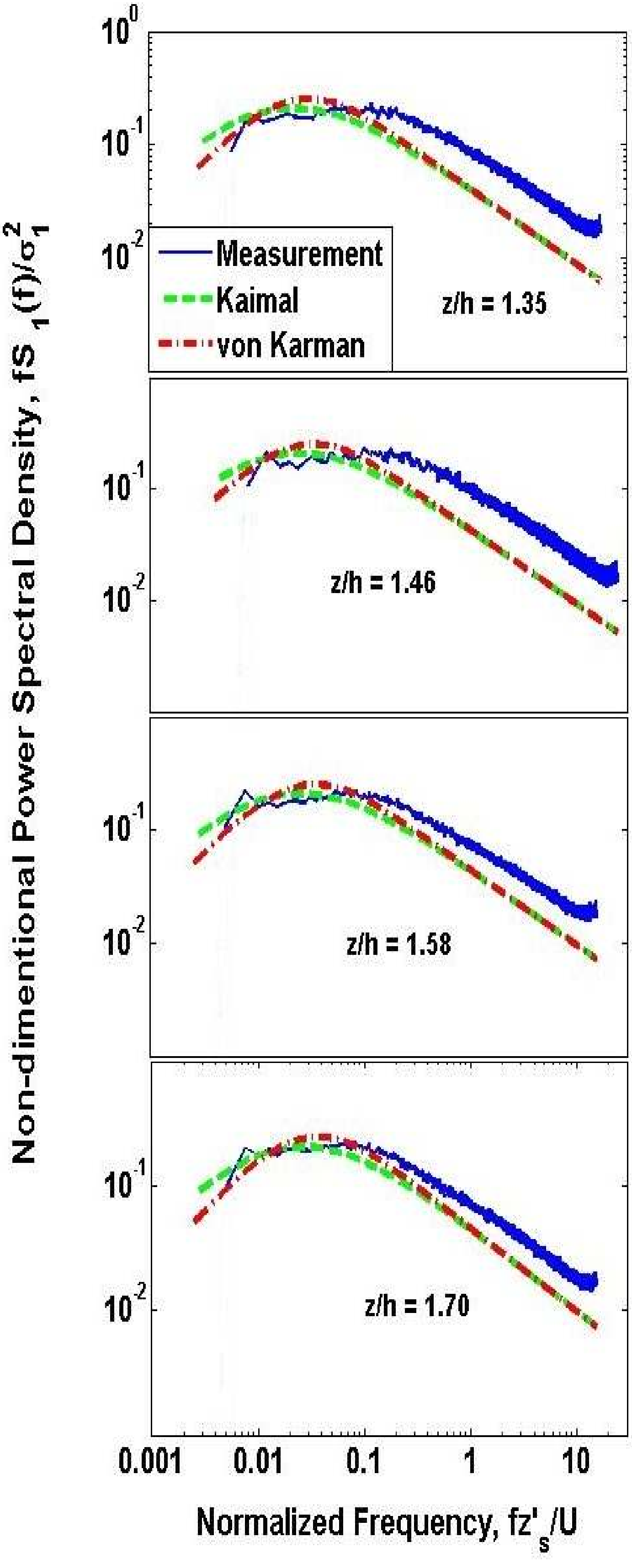

Figure 2a. Non-dimensional turbulence power spectral density of the **longitudinal** wind speed component for different heights above the rooftop of a warehouse in neutral atmospheric conditions

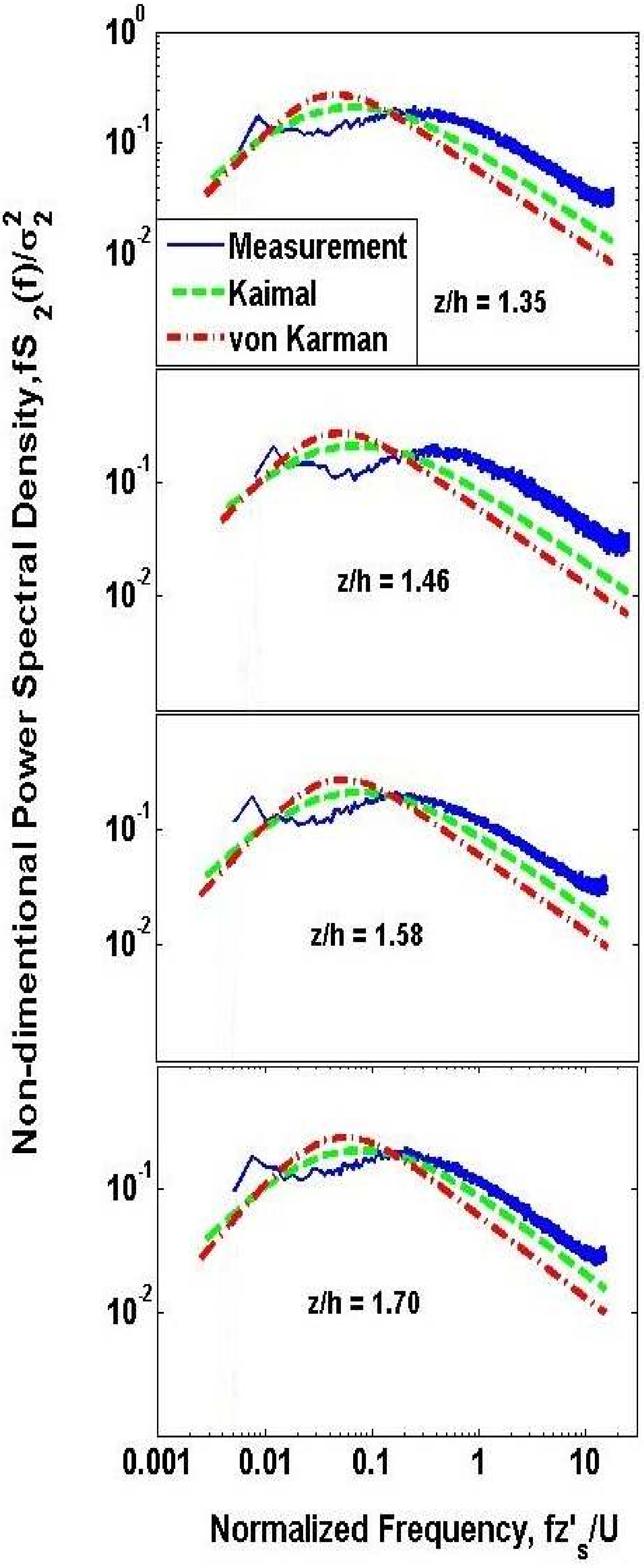

Figure 2b. Non-dimensional turbulence power spectral density of the **lateral** wind speed component for different heights above the rooftop of a warehouse in neutral atmospheric conditions

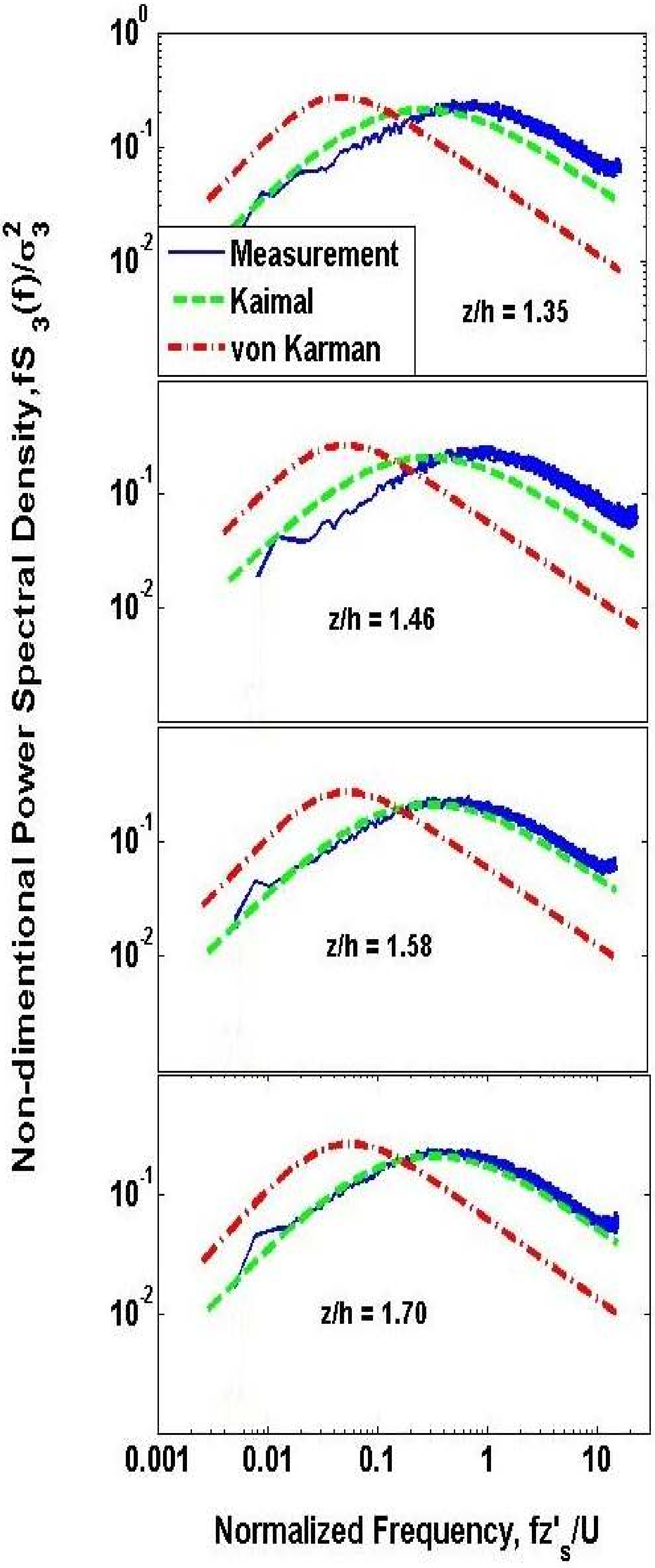

Figure 2c. Non-dimensional turbulence power spectral density of the **vertical** wind speed component for different heights above the rooftop of a warehouse in neutral atmospheric conditions

Table 1. L1 norm assessing the misfit of the von Karman and Kaimal spectra to the measured spectra

Height	Wind Com.	von Karman	Kaimal	No. of Records*
(*z/h* = 1.35)	Longitudinal	6.6887	6.7014	390
	Lateral	8.3837	5.1691	
	Vertical	13.5650	3.8250	
(z/h = 1.46)	Longitudinal	10.3630	10.3625	243
	Lateral	12.8987	8.3533	
	Vertical	20.4117	6.5988	
(z/h = 1.58)	Longitudinal	4.6472	4.6705	570
	Lateral	6.2437	3.4124	
	Vertical	10.4217	1.8474	
(z/h = 1.70)	Longitudinal	4.0499	4.0782	514
	Lateral	5.4584	2.6746	
	Vertical	9.7276	1.3012	

* Number of 10-minute records that were used in the averaging process.

4. Discussion

One likely reason for the inaccuracy of the Kaimal model in terms of predicting the magnitude of turbulence power spectra in the built environment, is that the Kaimal model as defined in IEC61400-2 assumes open terrain characteristics [7,8]. The parameter of length scale represents the size of turbulent eddies [13] and in the built environment the scale of turbulence due to local inhomogeneties would be expected to be markedly different to the scales of turbulence in the more uniform open terrain. Hence defining the length scale in terms of surface urban morphology may provide a more realistic estimation for use within the standard.

Currently the Kaimal model used in IEC61400-2 uses integral length scales as shown in Table 2, where the turbine is to be installed at a height z, less than 30 m (typical for a small wind turbine).

Table 2- Suggested integral length scales in the IEC61400-2 standard

	Velocity component index, k		
	1	2	3
Integral length scale, L_k	5.67*z*	1.89*z*	0.462*z*

A corrective approach for the application of the Kaimal model in the built environment is proposed, where, the longitudinal integral length scale from Table 2(5.67*z*) incorporates the effect of the building by substitution of *z* with *z* - *h* (height above roof). Lateral and vertical integral length scales are then estimated using ratios of length scales appropriate for the built environment ($\frac{L_2}{L_1} = 0.5$ and $\frac{L_3}{L_1} = 0.15$) from studies by Christen et al. above the rooftop of a street canyon [14].

Figures 3(a-c)) shows the results of comparing the new predictions from the corrected Kaimal model with the averaged values of the measured power spectra at the four different heights (see Figure 3a shows that the corrective approach suggested above results in more accurate predictions by the Kaimal model over a large range of frequencies for all three wind components in terms of the model's application to sites in the built environment. Note that the model results at *z/h* = 1.46 show the worst discrepancies with the measurements compared to the other studied heights although this may be due to the low number of data records at this height). Table 3 compares the values of the Misfit Function L_1 norm for the IEC standard (Kaimal model) approach and proposed (corrected Kaimal model) approach. It is clear that the suggested approach for calculating length scale results in a much lower Misfit Function L_1 norm than the current IEC standard approach for the Port Kennedy site.

In terms of the limitations of the study it must be noted that the corrected Kaimal model shows good agreement with measured data from just one rooftop location. In addition the measured data consisted of records over a period of 10 days taken at a specific time of the year.

6. Conclusion

The current IEC61400-2 standard uses stochastic turbulence models based on von Karman and Kaimal power spectra in order to simulate flow fields that are used to predict structural loading on small wind turbines. The suitability of these power spectra for simulating turbulence in the built environment for small rooftop wind turbines has been investigated by comparing the model spectra with measured data on the rooftop of Bunnings' warehouse at Port Kennedy in Western Australia. The power spectra of all three wind components in neutral atmospheric conditions at four heights above the rooftop are considered. The Misfit Function L_1 Norm was used to compare von Karman, Kaimal and measured power spectra, as an indicator of model suitability.

In the light of the limitations of this study the following conclusions can be drawn. In terms of general trends in the power spectral density functions, the von Karman and Kaimal spectra in predict longitudinal turbulence spectra in the built-environment reasonably well particularly for high frequencies whereas only the Kaimal model predicts the trends of the lateral and vertical wind components with any accuracy. In terms of the magnitude of the power spectra, , the von Karman and Kaimal spectra under estimate the measured values for all wind components although the; Kaimal spectra provides more realistic values than the von Karman spectra in terms of predicting the turbulence power spectra of lateral and vertical wind components in the built-environment. A corrected Kaimal model is proposed that incorporates the building height and typical length scale ratios in the built environment. The proposed model showed good agreement with measured data from the Port Kennedy site for all heights where there was sufficient measured data.

The corrected Kaimal model appears promising as a step forward on the path towards upgrading the existing standard with a dedicated design model for wind turbine manufacturers who intend their turbines to be used in highly turbulent sites such as the built environment. However, further research is needed as to whether the corrected Kaimal model will be appropriate for different rooftop sites. Further data is required on the ratios between lateral length scale value, vertical length scale value and longitudinal length scale value in the built environment. Suggested future work includes a comprehensive study including different measurement campaigns across different built-up areas to assess the suitability of different spectra models. In order to provide a uniform spectra for the built environment one option may be using the method, suggested by Coceal and Belcher, to derive canopy parameters from urban morphological data and use them to estimate spectral length scales in the built environment [15].

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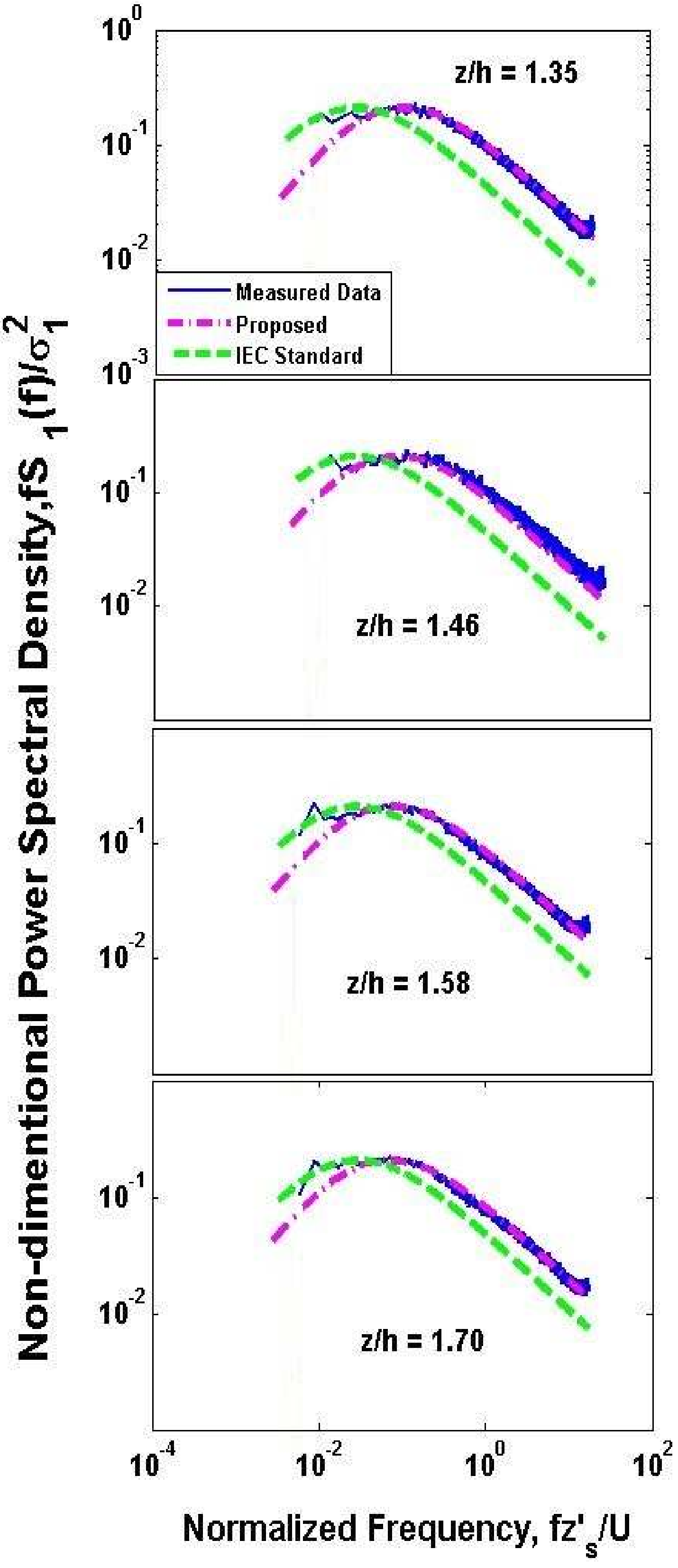

Figure 3a Comparison of measured non-dimensional longitudinal turbulence power spectrum density and predicted values by Kaimal model via IEC standard approach and proposed approach for different elevation above rooftop of warehouse in Port Kennedy, Western Australia

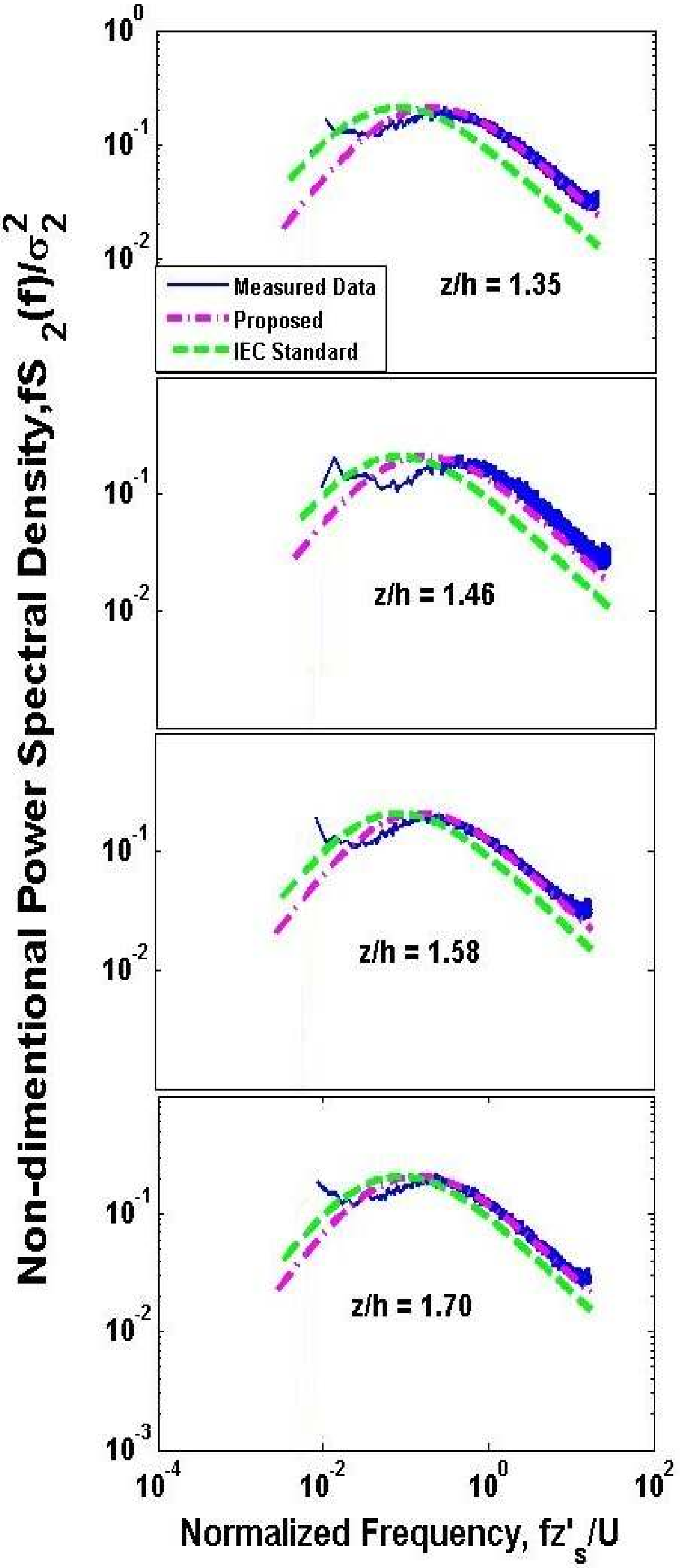

Figure 3b Comparison of measured non-dimensional lateral turbulence power spectrum density and predicted values by Kaimal model via IEC standard approach and proposed approach for different elevation above rooftop of warehouse in Port Kennedy, Western Australia (neutral atmospheric condition)

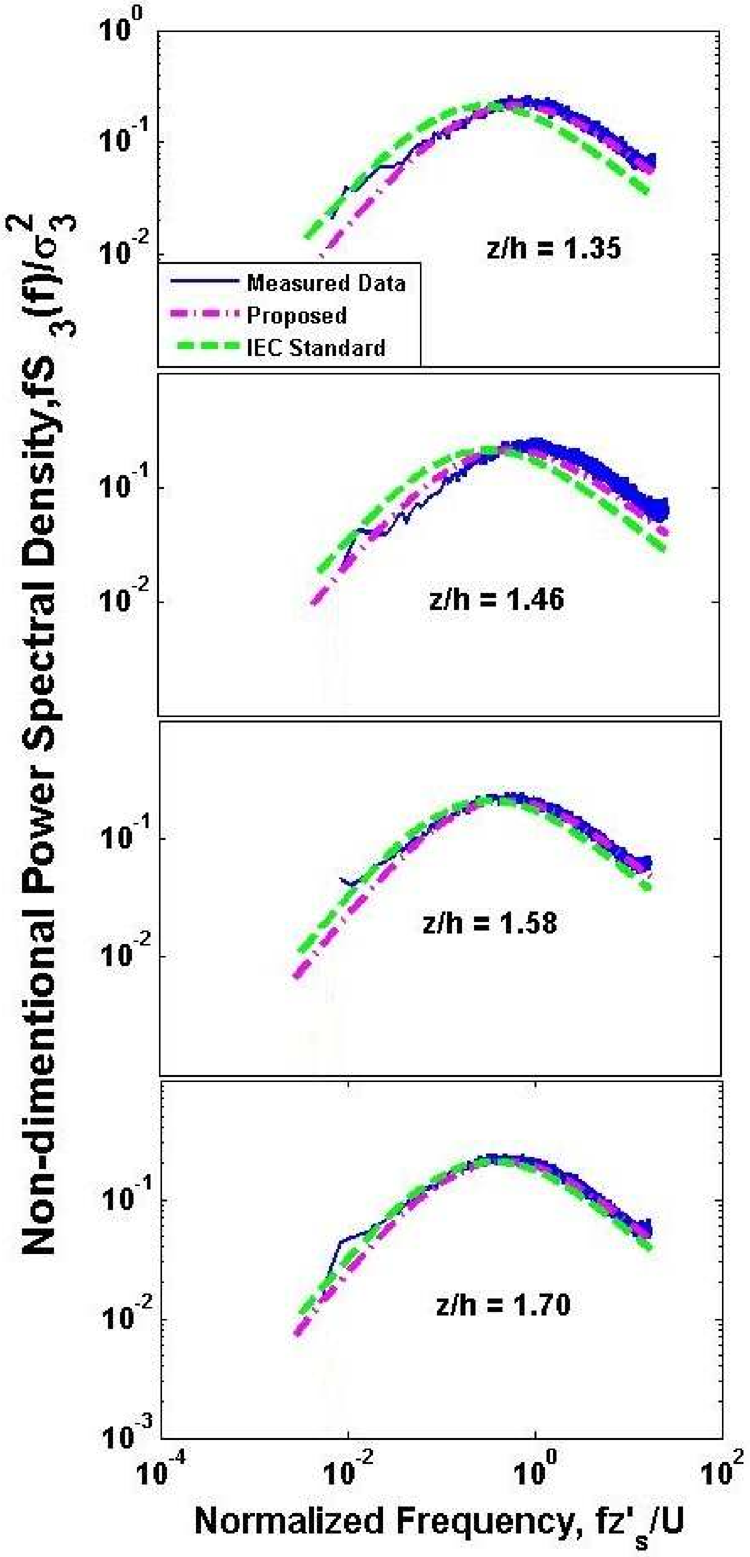

Figure 3c Comparison of measured non-dimensional vertical turbulence power spectrum density and predicted values by Kaimal model via IEC standard approach and proposed approach for different elevation above rooftop of warehouse in Port Kennedy, Western Australia (neutral atmospheric condition)

Table 3. L1 norm assessing the misfit of Kaimal spectra via IEC standard approach and proposed approach to the measured spectra

Height	Wind Com.	Kaimal **IEC Standard**	Kaimal **Proposed**	No. of Records*
(*z/h* = 1.35)	Longitudinal	6.7014	0.2293	390
	Lateral	5.1691	0.3666	
	Vertical	3.8250	0.3403	
(z/h = 1.46)	Longitudinal	10.3625	1.3613	243
	Lateral	8.3533	1.8585	
	Vertical	6.5988	1.7906	
(z/h = 1.58)	Longitudinal	4.6705	0.3423	570
	Lateral	3.4124	0.5707	
	Vertical	1.8474	0.3025	
(z/h = 1.70)	Longitudinal	4.0782	0.3156	514
	Lateral	2.6746	0.4636	
	Vertical	1.3012	0.2885	

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