Turbulence Length Scales in a Boundary Layer Wind Tunnel

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Summary

Turbulence length scales are important parameters affecting the aerodynamic characteristics and response of structures in wind flow. It is therefore essential to simulate the wind velocity profile models in scaling these turbulence length scale parameters as well as turbulence intensities when carrying out wind tunnel tests. Whilst there have been some full scale measurements of this length scale parameter, the scatter of the full scale data often presents difficulties in determining the effects of height and terrain roughness on this parameter. The present study attempts to derive this turbulence length scale from spectral measurements of wind velocity in a boundary layer wind tunnel at various heights for two different terrain roughness configurations. Using a large trip board in the upstream larger section of the wind tunnel to generate large turbulence length scales of magnitudes equivalent to scaled full-scale values for use in the test working section is discussed. Wind tunnel measurements are compared with the effective turbulence length scale, as given in AS1170, and the ESDU survey data for predicting the along-wind response of wind sensitive structures.

Introduction

The description of strong gusts in high winds can be characterized by the power spectral distribution of energy of the velocity fluctuations in the wind flow. There have been many suggested spectral forms expressing this universal wind spectrum in terms of a length scale L_h and variance σ_u^2 parameters at height h. The variance parameter can be expressed in terms of the turbulence intensity Iu and the length parameter can be obtained by matching the spectrum or integrating the spatial correlation coefficient of the turbulent components of wind speeds at two separated points. One of the spectral forms proposed by Harris [1] and commonly used in wind engineering for the longitudinal wind velocity spectrum is given by

$$\frac{nS_u(n)}{\sigma_u^2} = \frac{0.6\left(\frac{nL_h}{U}\right)}{\left[2+\left(\frac{nL_h}{U}\right)^2\right]^{\frac{5}{6}}}$$

This has a similar form of the Von-Karman spectrum of

$$\frac{nS_u(n)}{\sigma_u^2} = \frac{4\left(\frac{nL_x}{U}\right)}{\left[1+70.7\left(\frac{nL_x}{U}\right)^2\right]^{\frac{5}{6}}} \qquad \text{where } L_h \approx 11.88\, L_x$$

Similarly, the integral length scale obtained by integrating the spatial correlation coefficient of wind velocities at two points is numerically about one tenth of the turbulence length scale parameter L_h. In this paper, the turbulence length scale L_h values are evaluated by fitting the Von-Karman spectral form to the measured velocity spectra at various heights and in different boundary layer roughness configurations in a wind tunnel.

The effects of turbulence scale on bluff body aerodynamics and loading have been widely studied. For wind engineering applications generally, larger turbulent length scales would slightly increase the wind loads on quasi-static structures but would significantly reduce the dynamic loads on wind sensitive structures. The significance of this turbulence length scales on wind loads has been detailed by Harris [1]. Among very limited published full-scale data, Flay and Stevenson [2] measured some integral length scales in strong winds below 20m. More recently, Schroeder, Smith and Peterson [3] reported some full-scale measurements at a similar height with longitudinal turbulence intensity up to 16.9%. The integral scales were found to vary widely from 60m offshore up to 400m for onshore flow. Measurements of this turbulence length scale in boundary layer wind tunnels are also relatively limited. Schrader [4] has compared the computer simulation results with some wind tunnel measurements. However, the generation of large turbulence length scale is often limited by the size of the wind tunnel working section. Active modeling of turbulence in wind tunnels has been suggested by many researchers, such as Bienkiewicz, Cermak and Peterka [5] and Nishi, Kikugawa, Matsuda and Tashiro [6] to achieve large turbulence scale. In the present study, a relatively simple conventional method has been used to generate the turbulence with an addition of a large trip board in an upstream large tunnel section such that the length scales measured in the working section are large enough to be equivalent to full scale values for the 1/400 scale model measurements.

Experimental Technique

Measurements were made in the 2m by 2m expanded working section of the 450kW boundary layer wind tunnel at Monash University. Two models of the natural wind, typically 1/400 scale for smooth and rough terrains, were generated by flow over roughness elements augmented by a vorticity generator at the beginning of the wind tunnel working section. An additional large trip board, 500mm high, was installed in the upstream 4m by 3m working section to increase the turbulence length scale. Wind velocity time series from a hot-wire anemometer were recorded for lengths of 16384 samples at 1000Hz for various heights above ground. Power spectral densities of the time series were obtained using MATLAB averaging from FFT lengths of 256 with Hanning windows. The longitudinal velocity power spectrum was then fitted with a 4th order polynomial. A Von-Karman spectrum was shifted along the horizontal inverse wavelength axis by varying the length scale L_x variable until it matched with the fitted polynomial. Thus, the value of L_x was evaluated for each spectrum measured at various heights for both smooth and rough terrain wind models. Some data were measured without the additional large trip board to demonstrate its effects. The values of L_x were then compared with AS1170 [7] and ESDU data [8]. The AS1170 value of $L_h=(h/10)^{0.25}$ was only meant to be an approximation for use in a simplified form of the Gust Factor Analysis.

Results and Discussion

The longitudinal velocity power spectra for the smooth and rough terrain wind flow were plotted as a function of inverse wavelength in Figures 1 and 2 respectively. The longitudinal turbulence length scale is seen to increase as height increases, but the increase for the smooth terrain flow is shown to be smaller than that for the rough terrain flow.

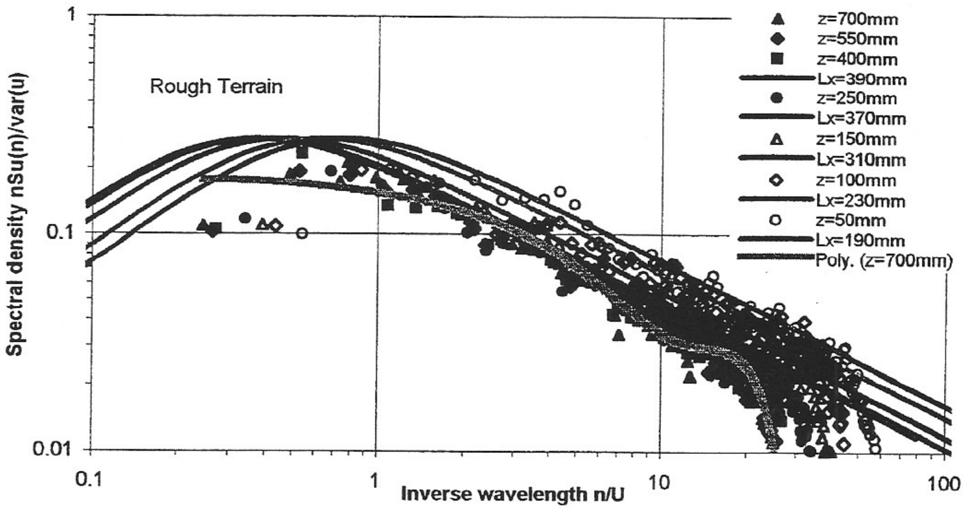

Figure 1 Longitudinal velocity spectra measured at various heights in rough terrain wind flow.

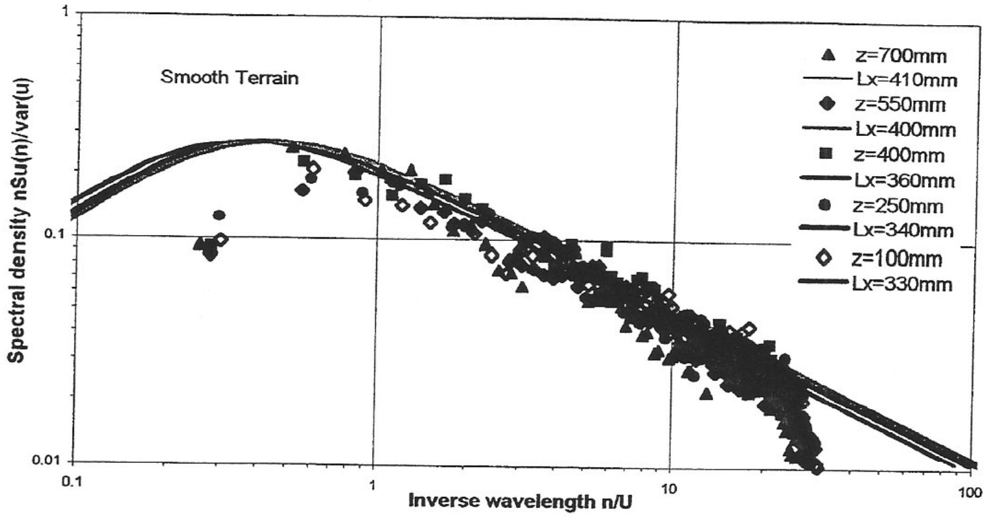

Figure 2 Longitudinal velocity spectra measured at various heights in smooth terrain wind flow.

The measured turbulence scale data, also expressed in equivalent full-scale values for the 1/400 scale model, are summarized in Table 1 below. The longitudinal velocity power spectra measured at a height of 400mm for both smooth and rough terrain flows with and without (shown with * in Table below) the additional large trip board in 4m by 3m section are shown plotted in Figure 3. The addition of a large trip board in an upstream working section is seen to generally increase the turbulence length scale by about 30%.

TABLE 1 Summary of measured turbulence length scale data for the 1/400 scale model and AS1170 values

	Rough Terrain Wind Model				Smooth Terrain Wind Model			
h (m)	U (m/s)	Iu	L_x(mm)	L_h(m)	U (m/s)	Iu	L_x(mm)	L_h(m)
280	16.0	0.14	390	**1850**	15.3	0.11	410	**1950**
220	14.9	0.16	390	**1850**	14.2	0.12	400	**1900**
160	14.5	0.18	390	**1850**	14.0	0.13	360	**1710**
100	11.5	0.22	370	**1760**	13.6	0.14	340	**1620**
60	10.0	0.25	310	**1470**				
40	9.0	0.27	230	**1090**	12.7	0.15	330	**1570**
20	7.2	0.33	190	**900**				
160*	14.6	0.17	290	**1380**	15.2	0.11	240	**1140**

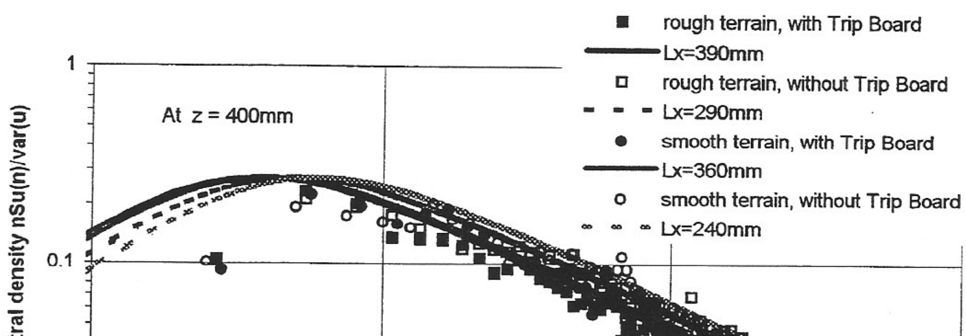

Figure 3 Longitudinal velocity spectra measured at 400mm with and without the additional trip board.

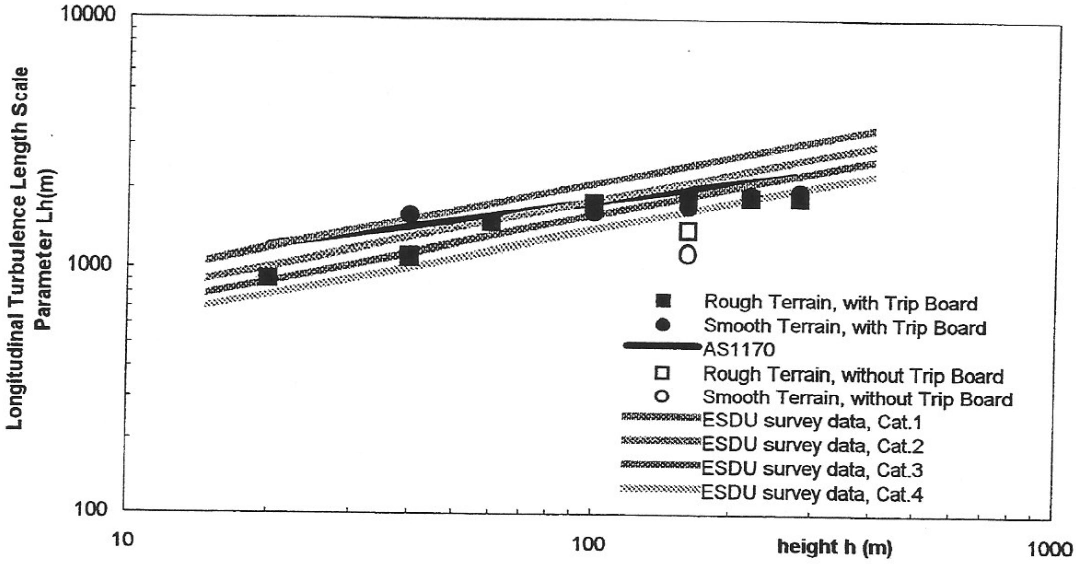

Figure 4 Longitudinal turbulence length scale L_h (m) as a function of height

The measured longitudinal turbulence length scale data are shown plotted in Figure 4 in terms of equivalent full-scale values based on the present 1/400 scale wind tunnel model studies. The effective turbulence length scale, as given in AS1170 Section 4.4.2, and the ESDU data were also plotted for comparison. The data measured in the boundary layer tunnel are seen to be generally in good agreement with the suggested full scale value for the 1/400 scale model.

Conclusions

Longitudinal turbulence length scales have been measured at different heights in a boundary layer wind tunnel for both smooth and rough terrain approach wind flows. The wind tunnel results have confirmed that the length scale generally increases as height is increased and is higher for smooth terrain than for rough terrain. The increase in length scale with height is seen to be smaller for the smooth terrain than for the rough terrain flows. At heights above 300m, the measured model turbulence length scales tend to become constant. Wind tunnel turbulence length scales can be increased by 30% by installing an additional large trip board in an upstream section, without using relatively expensive active devices. For the 1/400 scale model study, the wind tunnel results generally agree well with the AS1170 and ESDU data. Thus, by using an additional large trip board upstream of the working section, large full scale turbulence length scales can be properly modeled in 1/400 scale model studies.

Reference

[1] Harris R.I. (1986) Longer Turbulence Length Scales, *Jnl Wind Eng & Ind Aerodynamics*, 24, pp. 61-68.
[2] Flay R.G.J. and Stevenson D.C. (1988) Integral Length Scales in Strong Winds below 20m, *Jnl Wind Eng & Ind Aerodynamics*, 28, pp. 21-30.
[3] Schroeder J.L., Smith D.A. and Peterson R.E. (1998) Variation of Turbulence Intensities and Integral Scales during the passage of a hurricane, *Jnl Wind Eng & Ind Aerodynamics*, 77 & 78, pp. 65-72.
[4] Schrader P. (1993) Computing the statistical stability of Integral Length Scale measurements by Autoregressive Simulation, *Jnl Wind Eng & Ind Aerodynamics*, 46 & 47, pp. 487-496.
[5] Bienkiewicz B., Cermak J.E. and Peterka J.A. (1983) Active modeling of Large-Scale Turbulence, *Jnl Wind Eng & Ind Aerodynamics*, 13, pp. 465-475.
[6] Nishi A., Kikugawa H., Matsuda Y. and Tashiro D. (1999) Active Control of Turbulence for an Atmospheric Boundary Layer Model in a Wind Tunnel, *Jnl Wind Eng & Ind Aerodynamics*, 83, pp. 409-419.
[7] AS1170.2-1989 Australian Standard SAA Loading Code Part 2: Wind loads.
[8] ESDU data (The Engineering Sciences Data Unit, U.K.)