Wind Gust Factors with Various Turbulence Intensities and Length Scales

J C K Cheung and W H Melbourne

Department of Mechanical Engineering, Monash University, Victoria 3800, Australia

Abstract

Wind velocity data are often analysed to determine gust (peak) and mean (average) statistics for design to sustain in extreme conditions and for control to monitor these extreme levels through continuous measurement of the related means over a period of time. The relationship between the gust and the mean is simply expressed as the ratio of the gust to mean wind speeds, termed as the Gust Factor, G. The shorter the averaging period for the mean, the closer of the measured mean to the gust wind speed this becomes. The gust maximum value itself would also be higher when averaged over a shorter gust duration, t, or measured with higher turbulence intensity Iu or higher longitudinal length scale Lu_x. Therefore, it is important in the description of a Gust Factor to qualify the averaging duration both for gust and for mean wind speeds as well as the turbulence characteristics in the wind flow. This paper presents an analysis of wind tunnel data to relate the gust wind speed measurements and hence the Gust Factors for various averaging durations in neutral wind flow conditions of various turbulence intensities and longitudinal length scales. Some full scale wind data are also compared. The proposed relationship with respect to the hourly mean wind speed is as follows:

$$G = 1 + 0.075 \bullet Iu \bullet Lu_x^{0.25} \bullet [\ \ln(t/3600)\ ]^2 \bullet [\ 0.3 + 0.02\ \ln(t/3600)\ ]$$

Introduction

By mid-night 24 December 1974, Cyclone Tracy devastated Darwin leaving 48,000 people homeless with a maximum recorded wind gust of 217 km/hr (60.3 m/s) before the anemometer ceased functioning. This destructive wind was believed to have reached a sustained wind speed of 200 km/hr (55. 6 m/s) with short periods of gust closer to 300 km/hr (83.3 m/s), resulting in a gust factor G of at least 1.5. Thirty years on, not only the importance of design to extreme winds has been well considered, the prediction and description of the extreme winds have also been becoming more refined. Apart from the characterization with return periods, terrain roughness and height above ground to which the wind speed data correspond, the time durations upon which these wind speed data are averaged are also to be accurately defined.

In Australia, based on AS1170.2:2002, the basic design wind speeds are defined as 3 second mean maximum gust wind speeds at 10m height in Open Country terrain. The Dines anemometer, used by the Australian Bureau of Meteorology for some time in the past, has a response time which makes its maximum records equivalent to a 3 second mean maximum wind speed over a large wind speed range. However the cup anemometer used nowadays, having a response time varied approximately inversely with the mean wind speed related to the wind run, can normally measure mean wind speeds only. Other averaging durations commonly adopted in wind data analysis around the world range from 1 second to 10 minutes. These gust wind speeds are reproduced in wind tunnel testing within longer wind runs for over an hour of the full scale period. Thus the relationship between the mean wind speed averaged over some reference period and the gust wind speed averaged over some shorter duration within that period becomes essential in order to relate the wind tunnel measurements to the corresponding full scale design values. The adoption of 3 second mean maximum gust wind speed in the Australian Standard AS1170 and its relationship with the hourly mean wind speed can be traced from their relatively invariance over a very long record of several years as shown by the spectral gap of the full scale wind speed spectrum over an extended frequency range.

Previous Work

After Durst [1] analysis of wind speeds over various short periods of time from wind data at a height of 50ft (15.24m) at Cardington of open and flat terrain in the early sixties, there have been many empirical equations and data plots proposed to describe the variation of G with gust duration and turbulence characteristics.

Deacon [2] presented more data from different localities with various levels of terrain roughness. Brook and Spillane [3] derived the gust factors from an assumed spectral density function which allows for changes in stability and terrain. The equation proposed by Wieringa [4] implies a logarithmic dependence on the gust duration and a linear dependence on the turbulence intensity in terms of the terrain roughness length. Later in the late seventies, Greenway [5] derived a more complex equation by integrating the wind turbulence spectrum to further account for the structural dimension relative to turbulence length scale. A similar approach has also been adopted by ESDU [6]. However, in the eighties, Cook [7] simplified the previous equation with a straight line yielding similar results within a few per cent of the spectral approach as follows:

$$G\{t,z,z_0\} = 1 + 0.42\ (\sigma_u/\bar{U})\ \ln(3600/t) \qquad \text{where } G=1.6 \text{ for } t=1\text{s},\ z=10\text{m and } z_0=0.03\text{m}$$

During the last decade, a number of investigations on this relationship with validation of full scale data have emerged. Krayer and Marshall [8] have derived gust factors from four hurricanes data sets, for which the turbulence could be higher for these cyclonic winds. Based on these full scale data, they hypothesized an upward adjustment to the Durst gust factor curve, possibly due to the effect of turbulence. Other studies such as Ashcroft [9] and Richard Weggel [10] have shown a small variation of the gust ratio with wind speed. More recent analyses of full scale data by Xu and Zhan [11] for Typhoon York measured at Di Wang Tower, Shenzhen indicated that the gust factors fit with the equation as follows:

$$G(t) = 1 - 0.62\ (\ Iu\ )^{1.27}\ \ln(t/3600)$$

Also, Schroeder and Smith [12] presented wind gust factors from Hurricane Bonnie data with airport exposure. Although it has noted a wide variation of integral length scale throughout the storm, this effect on the gust factor data has not been identified. The data based on mean hourly wind speeds, however, agree well with the Krayer and Marshall's measurements with open terrain exposure. Xu and Chen [13] further reported more gust factor analysis on the Typhoon Victor data of various turbulence intensities recorded for the south west wind direction from the anemometers installed in the Tsing Ma suspension bridge in Hong Kong. For the high turbulence case of an averaged Iu of approximately 17.3%, the gust factors are shown to be higher than those of the Typhoon York data even though higher Iu of 19.6% were measured for the Typhoon York in Shenzhen. Although the corresponding turbulence length scales were not detailed, it is believed that the larger length scales corresponding to the open sea terrain at Tsing Ma could have increased the gust factor. A summary of the gust factor data analyzed from these previous studies is shown plotted in Figure 1 below.

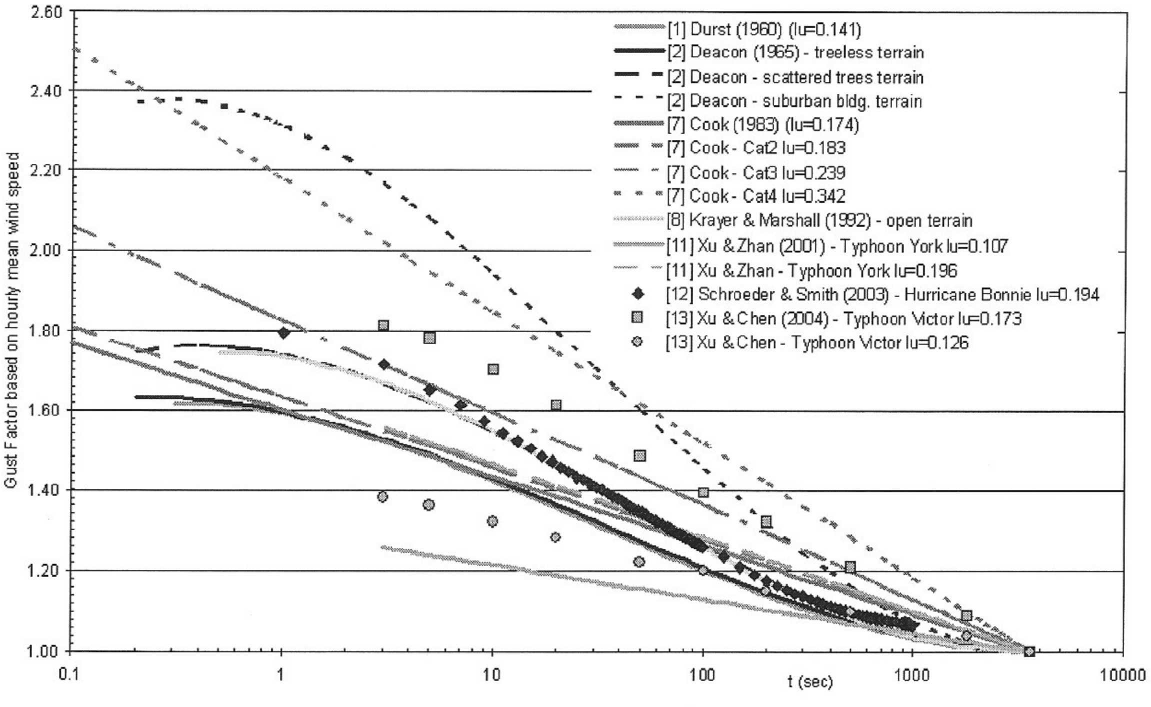

Figure 1 Gust Factors as a function of average time duration from previous studies

Present Analysis

To unravel the combined effects of turbulence intensity and longitudinal turbulence length scale on the gust factors of various averaging time durations, a series of 1/1500 model scale boundary layer wind profiles were measured over various terrain floor roughness in the 12m wide by 4m high wind tunnel working section at Monash University. The longitudinal turbulence length scale of full scale 100m, 300m, 600m, 900m and 1200m were generated by an oscillatory trip board activated at different frequencies in the return circuit of the wind tunnel. The experimental technique has been detailed previously by Cheung et al. [2003]. Each wind speed time series run sampled at 2500Hz is separated into full scale hourly segments with sub-segments of time durations of 0.1, 0.5, 1, 3, 5, 10, 20, 30, 60 and 600 seconds. The gust of different time duration is determined by the average within each sub-segment and a gust factor is the ratio of the maximum of these sub-segment averages within an hourly segment to the total mean of that hour. The 3 second gust for each case is shown to be approximately Gaussian distributed. The gust factor for different time duration is taken from the average of at least ten such hourly runs and presented for various longitudinal turbulence length scales in Figure 2 together with other full scale data. The example data set presented in this paper are chosen from the measurements at 10m high above ground for the suburban wind profiles with the power law exponent of 0.19 and the turbulence intensity of 0.2.

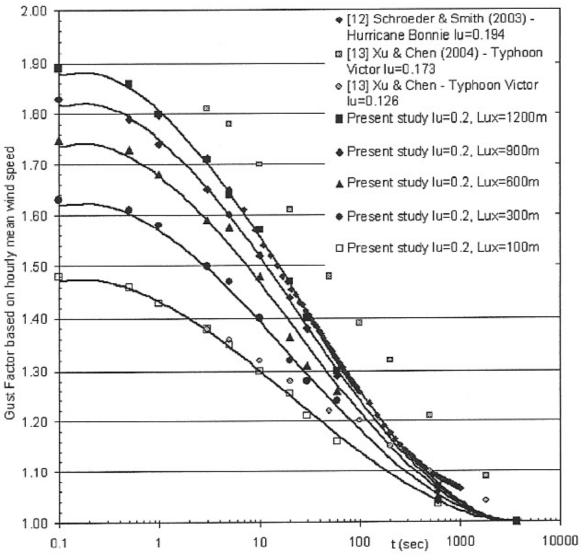

Figure 2 Gust factor as a function of time duration

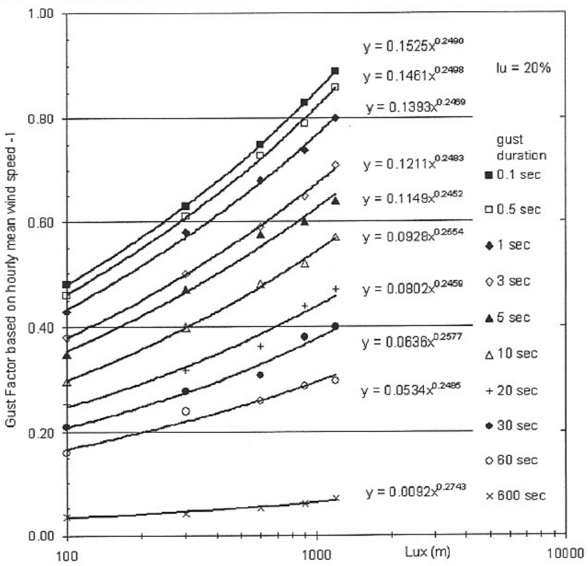

Figure 3 Gust factor as a function of longitudinal turbulence length scale

As shown in Figure 2, the data set for the longitudinal turbulence length scale of 1200m agrees well with the Hurricane Bonnie data. The Typhoon Victor high turbulence data could possibly correspond to even high turbulence length scale. By cross-plotting the fluctuating component, i.e. Gust Factor - 1, as a function of longitudinal turbulence length scale in Figure 3, this component of peak factor times the turbulence intensity is shown to vary with turbulence length scale to a power of approximately 0.25. Also, since the gust factor is better approximated by a cubic relationship than linear with ln(t/3600), the following equation is proposed:

$$G = 1 + 0.075 \bullet Iu \bullet Lu_x^{0.25} \bullet [\ \ln(t/3600)\ ]^2 \bullet [\ 0.3 + 0.02 \ln(t/3600)\ ]$$

Data generated by this equation are also shown in Figure 2 by the solid line curves, which fit with the measured data well. By using this equation to fit the full scale data with the corresponding turbulence intensity, it is shown that the Hurricane Bonnie data would correspond to a longitudinal turbulence length scale of 1300m and that the Typhoon Victor data would correspond to turbulence length scale ranging from 800m for the low turbulence intensity case to a few thousand metres for the high turbulence intensity case.

For comparison purposes with other full scale data, the gust factors determined from the above proposed equation are tabulated for various turbulence intensities and longitudinal turbulence length scales at 10m height as follows:

At z=10m gust duration t (sec)	Iu=0.157 (Cat.1) Lux=1500m	Iu=0.183 (Cat.2) Lux=1300m	Iu=0.239 (Cat.3) Lux=1100m	Iu=0.342 (Cat.4) Lux=900m
0.5	1.71	1.80	2.00	2.36
1	1.67	1.75	1.94	2.28
2	1.62	1.70	1.87	2.18
3	1.58	1.66	1.82	2.12
5	1.53	1.60	1.75	2.02
10	1.46	1.52	1.65	1.89
20	1.39	1.44	1.55	1.74
30	1.34	1.39	1.48	1.66
60	1.27	1.30	1.38	1.51
600	1.06	1.07	1.09	1.12
3600	1.00	1.00	1.00	1.00

Conclusions

Neutral boundary layer wind profiles have been measured in a wind tunnel in terms of wind speed time series for various terrain floor roughness and longitudinal turbulence length scales. The gust factors based on the hourly mean wind speed have been determined by direct averaging over the gust duration and data at 10m height full scale are presented in this paper. The gust factors were shown to increase with turbulence intensity and longitudinal turbulence length scale but decrease with the gust duration. A relationship of these effects to the gust factor is proposed and using this equation, values of gust factors for different turbulence intensities and length scales are tabulated. Some full scale data are also compared.

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