

## Gust Wind Speeds for Design of Structures

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This paper defines the peak gust wind speeds specified in applications related to building design and meteorology. The origin of the basic peak gust speed in the Australian Wind Loading Standards since 1971, derived from the Dines anemometer, is discussed, and the response of that anemometer to gusts is compared with the recording system in Automatic Weather Stations (AWS) based on 3-cup anemometers with a 3 s moving average filter that have replaced the Dines since the early 1990s. This later system is shown to significantly attenuate the high frequency wind fluctuations, and hence record lower gust wind speeds than the earlier Dines. A method for comparing gust wind speeds of different durations and for making wind data compatible with AS/NZS 1170.2 and other standards and codes is given.

**Keywords:** Gust wind speed, Standard, Code, Dines, 3-cup anemometer.

### Introduction

The “wind speed” for structural design and for categorising the intensity of, a windstorm is specified as a gust wind speed in the longitudinal or along-wind direction and is recognised as having a time averaged mean speed with turbulent fluctuations about this mean. This paper analyses the turbulent near-surface wind speed in “strong” wind conditions. The logarithmic boundary layer profile under neutral stability conditions represented by Deaves and Harris (1978) is the basis of the wind speed data and associated terrain categories given in the Australian/New Zealand Standard for Wind Actions, AS/NZS 1170.2 (2011) and its predecessors. The basic design wind speed in AS/NZS 1170.2 is based on the statistical analysis of historical peak daily wind measurements from the Bureau of Meteorology Dines anemometers. This is now defined as ‘a 0.2 second gust’ following the findings from the project by Ginger *et al.*, (2011). Holmes and Ginger (2012) showed that the equivalent moving averaging time for the damped resonant response of the Dines anemometers in relation to the maximum gusts produced is equivalent to about 0.2 s. They also produced factors to convert gust wind speeds currently recorded by the Bureau (using 3 cup anemometer and 3s averaging) to a gust with an equivalent averaging time of 0.2 s. The previous versions of the Standard incorrectly referred to ‘a gust of 2 to 3 seconds duration’ as the basic wind speed, which originated from the report by Whittingham (1964).

This paper discusses the gust speeds used for calculating design wind loads from AS/NZS 1170.2, and provides a means of analysing wind speed data from other sources for compatibility with the Standard. The effect of filtering on the gusts produced by the Bureau’s Automatic Weather Stations, since about 1990 with typical cup anemometers and 3 s average filtering is discussed. A method for correcting this gust data to make it compatible with AS/NZS 1170.2 is presented.

### Wind Speed

As detailed by Harper *et al.* (2010), the variation of longitudinal wind speed with time  $t$ ,  $u(t)$  can be represented as the sum of the mean wind speed  $\bar{U}$ , averaged over a time-span  $T$  and a fluctuating component  $u'(t)$  about the mean such that:

$$u(t) = \bar{U} + u'(t). \quad (1)$$

The expected maximum gust in a wind record with a mean value of  $\bar{U}$ , a standard deviation of  $\sigma_u$  is then related by the following:

$$\hat{U} = \bar{U} + g\sigma_u. \quad (2)$$

Here,  $g$  is the expected peak factor. A non-dimensional form of the variability is termed the turbulence intensity,  $I_u = \sigma_u/\bar{U}$ .

The relationship between the mean wind speed and the gust speed is often expressed in terms of a gust factor  $G$ :

$$G = \hat{U}/\bar{U} = 1 + gI_u. \quad (3)$$

Using this approach, values for  $G$  can be obtained for appropriate values of  $I_u$  and a statistically-based estimate of  $g$ . The most complete theoretical description is summarised by ESDU (2002), which is based on the original statistical approach by Davenport (1964) as augmented by the analyses of Greenway (1979). This approach considers the sampling of independent gust episodes from a pre-determined (i.e. von Karman) spectrum of the natural wind, associated with the chosen averaging period,  $T$  and gust duration,  $\tau$ . Then, with the assumption of a Gaussian parent distribution, this can be shown to produce an Extreme Value Type I (or Gumbel) distribution for the maximum gusts and the mean of this distribution is then taken as the expected value.

The value of turbulence intensity, peak factor, gust factor and the gust wind speed are all dependent on the instrument response (associated filtering) and any additional moving average filtering, and is also sensitive to the choice of  $T$ . Wind velocity fluctuations will generally contain energy to  $> 5$  Hz. Normally,  $T$  is chosen to be hourly in synoptic environments and usually not less than 10 min. Hence, reference here to  $I_u$  implies a base reference  $T \geq 600$  s as a suitably stable estimate of the "true mean" wind speed. In addition to the increase in official meteorological stations worldwide, the recent development of mobile instrumented towers in the USA (e.g. Schroeder *et al.* 1998, Masters *et al.* 2005) has led to a greater capture rate of data from windstorm conditions. However, there are questions as to the homogeneity of all these data sets and the use of, related curves such as those by Durst (1960) for making direct gust comparisons. Furthermore, estimation of ground level gust wind speeds in tropical cyclones that are based on techniques derived by Dvorak (1984) and subsequently used for risk studies in parametric models such as those based on Holland (1980) are also normally calibrated to measurements from anemometers and therefore are influenced by their response. Hence, the data analysed and reviewed by Harper *et al.* (2010) must also be re-assessed for consistency.

The Dines anemometer was the main instrument for measuring wind gusts recorded by the Bureau of Meteorology in Australia from the 1930s to the 1990s. These analog recording pitot-static sensors have been replaced by more compact self-contained cup anemometer sensors with digital recording systems that have different response characteristics. Anemometers are usually calibrated by their manufactureres to satisfactorily provide a mean wind speed averaged over several minutes. However, there is usually limited data on the dynamic response characteristics of anemometers in turbulent winds (e.g. Greenway 1979; Beljaars 1987, Miller 2007). Cup anemometers widely used to record wind speeds inherently apply some filtering, due to e.g. the mechanical inertia of cups, thus influencing the measured gust wind speed and turbulence intensity.

### Wind Speed - Random Process Theory

Random process theory can be used to predict the wind gust factors recorded by anemometers in a turbulent wind of known intensity and spectral density. It can also be used to derive the gust factor for the wind spectral density 'filtered' by a moving average filter with a defined averaging time of  $\tau$  s. The application to wind engineering was pioneered by Davenport (1961, 1964), and is summarized by Holmes (2007).

Using this approach, the spectral density of the wind turbulence is modeled using the well-known von Karman form, which, in non-dimensional form, can be written as follows (see section 6.2.2 in AS/NZS 1170.2):

$$n.S_u(n)/\sigma_u^2 = 4 \left( \frac{nL_u}{\bar{U}} \right) / \left[ 1 + 70.8 \left( \frac{nL_u}{\bar{U}} \right)^2 \right]^{5/6} \quad (4)$$

Here,  $n$  is frequency,  $S_u(n)$  is the spectral density of the longitudinal velocity,  $u$ , and  $\bar{U}$  is the mean wind speed (usually averaged over ten minutes to one hour to be representative).  $L_u$  is an integral length scale, and  $\sigma_u$  is the standard deviation of velocity, which can be obtained from the mean wind speed and the intensity of turbulence (i.e.  $\sigma_u = I_u \times \bar{U}$ ). For a height of 10 m above ground, AS/NZS 1170.2 gives a value for  $L_u$  of 85 m.

An anemometer, when responding to wind gusts, 'filters' the atmospheric turbulence with a transfer function  $|H(n)|^2$ . The cycling rate or 'average frequency',  $v$ , of the filtered process can be calculated as follows (e.g. Davenport, 1964):

$$v = \left\{ \frac{\int_0^{\infty} n^2 . S_u(n) . |H(n)|^2 dn}{\int_0^{\infty} S_u(n) . |H(n)|^2 dn} \right\}^{1/2} \quad (5)$$

The expected peak factor can be calculated using the well-known formula for Gaussian random processes of Davenport (1964):

$$g = \sqrt{2 \log_e vT} + \frac{\gamma}{\sqrt{2 \log_e vT}} \quad (6)$$

where  $\gamma$  is Euler's Constant (0.5772).

The expected gust factor can be obtained from,  $G = 1 + g\sigma_{u,f}/\bar{U}$ , where  $\sigma_{u,f}$  is the standard deviation of the filtered signal given by:  $\sigma_{u,f} = \left\{ \int_0^{\infty} S_u(n) . |H(n)|^2 dn \right\}^{1/2}$ .

The dynamic responses of the low- and high-speed Dines were presented as their transfer function  $|H(n)|^2$  by Miller *et al.* (2013). Holmes and Ginger (2012) then showed that the basic wind gust in AS/NZS1170.2 is an equivalent moving average time of 0.2 seconds as it is equivalent to the expected maximum gusts recorded by both the low- and high-speed Dines anemometers.

A cup anemometer's response is given in terms of a distance constant,  $D$  which represents the "length of wind" required to respond to a stepped change in speed (e.g. Kristensen 1993). The distance constant depends largely on the mass and inertia of the rotating parts of the anemometer. In the case of the Synchrotac 706 anemometer, currently the most common type used in AWS in Australia, the value of  $D$  is about 13 m. The corresponding time constant may be found by dividing the distance constant by the mean wind speed. For the case of the cup anemometer, the transfer function can be represented by :

$$|H_1(n)|^2 = 1 / \left[ 1 + \left( \frac{2\pi nD}{\bar{U}} \right)^2 \right] \quad (7)$$

Shortly after the introduction of AWS with cup anemometers (in about 1990), the Bureau of Meteorology incorporated a 3 s moving average filter based on a WMO specification (Beljaars, 1987), in addition to the inherent filtering of the cup anemometer itself. The moving average process is represented in the frequency domain by the following transfer function where,  $\tau$  is the moving average time.

$$|H_2(n)|^2 = \left( \frac{\sin(n\pi\tau)}{n\pi\tau} \right)^2 \tag{8}$$

The combined transfer function obtained by the double filter effect of the anemometer and the moving average is given by,  $|H(n)|^2 = |H_1(n)|^2 \cdot |H_2(n)|^2$

The Von Karman wind velocity spectrum for an approach wind flow with a mean wind speed of  $30 \text{ ms}^{-1}$  and turbulence intensity of 18.3% for Terrain Category 2 flow at 10 m height (see Table 6.1 in AS/NZS1170.2), and the output from a 3-cup with 3 s moving average filter are shown in Fig. 1. The ‘double filtering’ results in a severely attenuated wind spectrum at the high-frequency end, and produces maximum gusts significantly less than those previously recorded by the Dines anemometers that form the statistical basis for the regional peak gust in AS/NZS 1170.2. It should be noted that the 3 s moving average filter completely suppresses fluctuations with frequencies of 0.333 Hz (i.e. periods of 3 s) and its integer multiples, and severely attenuates all fluctuations with frequencies greater than 0.2 Hz.

The response characteristics of the raw Dines signal and a 3-cup anemometer with a 3 s moving average filter are compared by calculating the relevant parameters presented in Table 1. The 3-cup with 3 s moving average filter significantly attenuates the fluctuations and gives a gust factor of 1.43 compared to 1.62 from a Dines, which is equivalent to a 13% discrepancy in the expected gust wind speed. Miller *et al.* (2013), applying similar random process theory to that

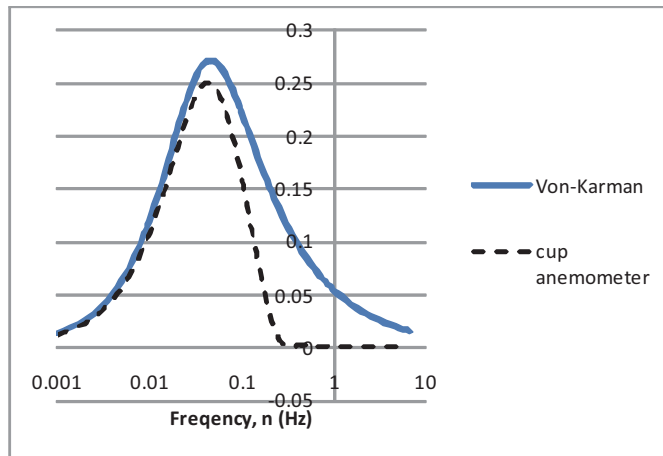


Fig. 1. Effect of 3 s moving average filtering on the wind spectrum as ‘seen’ by a cup anemometer ( $\bar{U} = 30 \text{ ms}^{-1}$ ).

Table 1. Calculated response parameters of 3-cup (with 3 s moving average) and Dines anemometers.

	3-cup	Dines
Cycling rate (Hz)	0.065	0.394
Std. deviation (m/s)	4.387	5.314
Peak factor, $g$	2.918	3.481
Gust factor, $G$	1.427	1.617

given in this paper, show that a 3 s moving average filter applied to the output from a cup anemometer, underestimates the peak gust recorded by a high-speed Dines by between 11 and 19%. This is also comparable with the 15% higher peak gust recorded by the Dines situated about 20 m away from the 3-cup anemometer during Tropical Cyclone ‘Vance’ at Learmonth, in 1999 noted by Reardon *et al.* (1999). Similarly, Boughton *et al.* (2011) found that the Dines gave a peak gust wind speed about 20% higher than the nearby 3-cup at Townsville, during Tropical Cyclone Yasi in 2011.

Holmes and Ginger (2012) provide factors for correcting the peak gusts produced by the current measurement system in Australia from a 3-cup anemometer, with associated 3 s moving average filter to a 0.2 s gust as required for compatibility for structural design with AS/NZS 1170.2, or in conjunction with the Standard. The correction factors require increases in the recorded gusts from 8% to 16%, depending on the mean wind speed and turbulence intensity. Incorrectly applying a 3 s gust wind speed instead of the 0.2 s gust can hence produce loads that are 35% lower.

### AS/NZS1170.2 and Other Codes/Standards

The mean wind velocity profile in AS/NZS1170.2 is based on extensive full scale data and the Deaves and Harris (1978) model logarithmic law. In addition, the model determines the turbulence intensity from which the gust wind speed is related to an “hourly” mean wind speed by applying a peak factor of 3.7. Using random process theory, described here, Holmes and Allsop (2012) calculated the expected peak factor for wind turbulence with the von Karman spectral density, as a function of the non-dimensional reduced velocity ( $\bar{U}.T/L_u$ ) and  $(T/\tau)$ . Fig. 2 shows the expected peak factor plotted against reduced velocity for various values of  $T/\tau$ , where  $\tau$  is the moving average time.

For the commonly assumed values of  $T$  and  $\tau$  of 3600 and 3 s respectively, the peak factors are given by the line for  $(T/\tau)$  equal to 1200 in Fig. 2. It can be seen that for this ratio, the peak factor is about 3.0 for typical European design wind speeds but reduces to as low as 2.0 for higher values of reduced velocity. However, for higher values of  $(T/\tau)$  the peak factor is relatively constant with varying wind speed. ESDU (2002) has graphs of peak factor against averaging time for particular values of reduced velocity. For  $T$  and  $\tau$  of 3600 and 0.2 seconds respectively, the peak factors given by the line for  $(T/\tau)$  equal to 18000 in Fig. 2, show that a peak factor of about 3.7 is applicable for data stipulated in AS/NZS1170.2.

Another consideration in redefining the gust duration, was the effective frontal area over which the gust could be considered to act. This effective area of a maximum gust was estimated by apply-

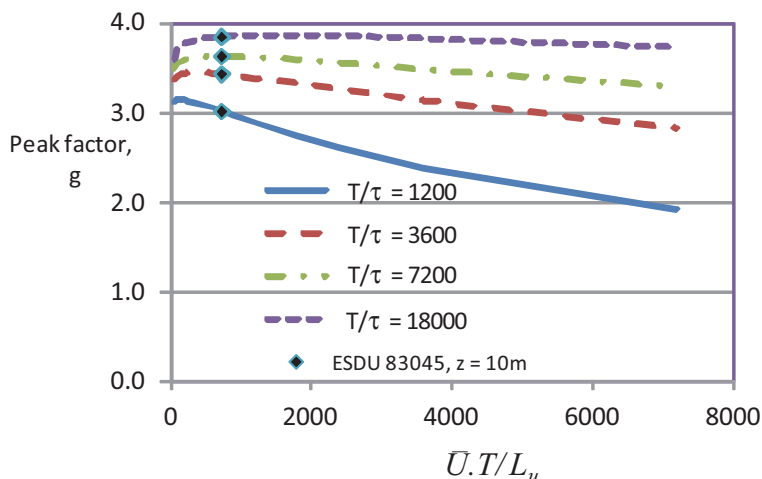


Fig. 2. Expected peak factors vs. reduced velocity for four values of the ratio of sample time to moving average time.

ing a transfer function representing an ‘aerodynamic admittance’ based on numerous measurements on small plates with effective area  $A$  in grid turbulence (Vickery, 1968) given in Equation 9.

$$|H(n)|^2 = \frac{1}{\left[1 + \left(\frac{2n\sqrt{A}}{\bar{U}}\right)^{4/3}\right]^2} \quad (9)$$

Using Equation 9 and the methodology above, equivalent frontal areas for the 0.2 s gust have been derived by matching the calculated expected gust factors, for a range of mean wind speeds and turbulence intensities. These are shown in Table 2, and indicate that the effective frontal area increases with mean wind speed. For the range of mean wind speeds of interest for structural design of 20 to 50  $\text{ms}^{-1}$ , the frontal area of 5  $\text{m}^2$  to 40  $\text{m}^2$  approximates that of a small building such as a shed or garage. Road sign “windicators” used for estimating wind speeds by Ginger *et al.* (2007) provide gust wind speeds that closely approximates Dines anemometer measurements, as was assumed by Boughton *et al.* (2011).

In the United States, ASCE 7 (2010) changed to a peak gust wind speed metric from the previous ‘fastest mile’ definition in 1995, and similar gust speeds have continued since then. The analysis for non-hurricane regions used gusts recorded primarily from cup anemometers with a corresponding ‘time constant’ (roughly equivalent to the gust duration) of about 0.5 s. However, design peak gust speeds in the hurricane-affected regions of the US have been generated by simulation methods, with gust factors equivalent to 3 s moving average gusts, similar to the WMO definition. In the Eurocode (2005) for wind actions a ‘peak velocity pressure’ is calculated, based on a peak factor,  $g$ , of 3.5. It can be shown, using the methods discussed, for  $T = 600$  s, that this is also approximately equivalent to a 0.2 s moving average gust. The International Standard for wind actions (ISO, 2009), allows for conversion between a range of averaging times, but the main body of the Standard is based on a 3 s moving average gust speed defined similarly to the WMO definition, with a peak factor of 3.0 for a 1 h reference period.

**Table 2.** Equivalent frontal area centred at 10 m height corresponding to a 0.2 s gust.

$\bar{U}$ (m/s)	A ( $\text{m}^2$ )
20	7.6
25	11.3
30	15.6
35	20.6
40	26.2
45	32.3
50	39.1

## Conclusions

The design wind speed in the Australian Standards since 1971 were derived from the statistical analysis of peak daily gusts derived from the Dines anemometer. The cup anemometers with an associated 3 s averaging that have replaced the Dines since the early 1990s are shown to significantly attenuate the high frequency wind fluctuations and hence record a lower gust wind speed. The peak gust in AS/NZS 1170.2 is defined as a ‘0.2 s gust’, based on a moving-average definition of the gust duration equivalent to the response of the Dines. These gusts act on an effective averaging area between 5 and 25  $\text{m}^2$ .

The random process approach to estimating gust factors and Dines/cup gust ratios gives good agreement with measured values of gust ratios from the two measurement systems in several windstorms. It enables adjustment for varying parameters such as mean wind speed,



turbulence intensity, turbulence length scale, and the distance constant of the cup anemometer. The effect of applying a 3 s moving average filter to the 3-cup anemometer output, as recommended by the WMO, is to truncate the high-frequency end of the wind spectrum and greatly increase the difference in peak gusts between the 0.2 sec Dines-equivalent gust and 3-cup anemometers. Adjustment factors are dependent on the mean wind speed and turbulence intensity. Generally, gust wind speed data recorded by the Bureau of Meteorology from automatic weather stations, since about 1990, will need adjustment to be compatible with the Standard.

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