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Response Characteristics of Anemometers Used in New Zealand

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ABSTRACT

Several types of cup anemometers with considerably different designs and recording systems have been used in New Zealand during various periods. The changes in instrumentation and observing practices have affected the recorded wind speeds and resulted in inhomogeneous historical data. In this study, wind-tunnel tests were carried out to compare the response characteristics of three main cup anemometers utilised in New Zealand, using random process and linear systems theory. Different parameters, such as distance constants of the anemometers, peak and gust factors, are determined at different turbulence intensities and wind speeds. The average expected gust factor ratios between these anemometers are calculated, and the effect of applying the WMO-recommended 3-s moving average on the recorded gusts are investigated. It is generally found out that the Vector and Vaisala anemometers record 7%-13% and 9-15% higher gusts than those of the Mark II Munro anemometer, respectively, and applying the WMO 3-s moving average reduces these differences to about 1% to 6%.

1. Introduction

The heavy Mark II Munro cup anemometer, hereafter referred to as MK II, with a chart recorder was the primary wind speed recording instrument in New Zealand until it was replaced by light Vector A101 and Vaisala WAA151 cup anemometers with digital recorders in the 1990s. Significant differences between the old and new systems, in terms of the response characteristics of the instruments, observation practice and signal processing methods, considerably affected the historical wind data over the period of the record, particularly gust wind speeds, which are extremely sensitive to the anemometer response characteristics. For example, Safaei Pirooz and Flay (2017) illustrated these effects on daily and annually recorded wind speeds at several meteorological stations in New Zealand. Figure 1 shows a discontinuity in the annual gust speeds recorded during the 1990s at Auckland airport resulting from changes in the instrument and observing practices. In addition, the adoption of the World Meteorological Organisation (2014)(WMO) 3-s moving average gust speed, which was introduced into New Zealand in the 1990s, has further affected the historical data.

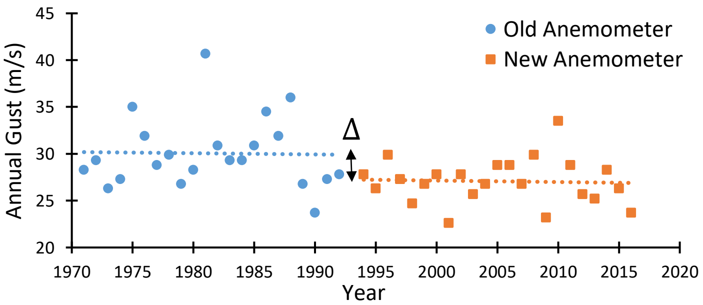

Fig. 1. Annual maxima recorded by the old and new anemometer systems at Auckland airport (Safaei Pirooz and Flay 2017)

Long-term historical gust and mean wind data are essential in many applications, including the determination of design wind speeds and wind loads, and assessment of climate change. Therefore, it is of great importance to carefully evaluate the historical records of wind speeds, detect and remove all the artificial shifts resulting from various factors, such as changes in anemometer height, terrain conditions, and changes in instrumentations.

Although the effects of terrain roughness and anemometer height have long been recognised and taken into account, changes in both recording instruments and observing practices have sometimes been ignored (Miller et al. 2013). In particular, to date in New Zealand, no study has been carried out to investigate the effects of instrumentation types on the historical wind data. Here we aim to experimentally analyse the dynamic and frequency responses of three important cup anemometers that have been utilised in New Zealand, and compare their response characteristics using random process and linear systems theory. Various parameters of the anemometers, such as distance constant, cycling rate, power spectral density, and peak and gust factors are obtained, based on wind-tunnel measurements. Calculating the gust factor ratios between the anemometers allows us to rationally compare wind data recorded on the former and current instruments, and to homogenise the historical wind data for further meteorological and climatological studies. In addition, the effects of applying the 3-s moving average filter on the recorded data are investigated.

2. Response Characteristics of Cup Anemometers

Cup anemometers have been used for many years to measure wind speeds and understand the behaviour of wind near the Earth's surface. Cup anemometers carry many advantages, which are important, particularly when they are used in the field. They are robust and can be used for many years with a minimum maintenance, they have a symmetry axis which means they are equally sensitive to winds from all directions, the calibration is very linear, and the measuring accuracy is high so that the mean speed can be measured within about 1% (Kristensen, 1999). However, when dealing with long-term historical data, there are inevitable breakpoints in time series resulting from changes in either instrumentation type or observing practices, or the occurrence of both simultaneously. In order to take account of these changes and to produce homogenised historical wind data, several approaches have been proposed. One of the simplest methods is to compare the mean and gust wind speeds measured by the old and new systems and to obtain correction factors (Smith 1981). Another approach involves taking simultaneous measurements with both the old and new instruments and to calculate the correction factors. A more accurate and sophisticated approach, as proposed by Davenport (1964), is to employ random process and linear systems theory along with knowledge of the frequency response characteristics of both the instrumentation and observing practices, to find a set of correction factors. Using the last approach, Miller et al. (2013) compared the response of the Dines anemometer and Synchrotac 706 cup anemometer to gusts, and calculated the gust factor ratios. Masters et al. (2010) utilised this approach to find correction factors following the changeover from Belfort cup anemometers to Vaisala ultrasonic anemometers in the United States.

Random process theory can be used to predict the wind gust factors recorded by different types of anemometers in a turbulent wind of known intensity and spectral density. In addition, the effects of a moving average filter on the gust factor can be investigated using this theory. Davenport (1964) defined the mean gust factor (G) occurring over some time period T in Eq. (1),

$$G = 1 + g\frac{\sigma_u}{\overline{U}} \qquad (1)$$

where g is a peak factor, σ_u is the standard deviation of the along-wind speed fluctuations about the mean wind speed during period T, and $\overline{U}$ is the mean speed. g can be calculated using the formula for Gaussian random processes (Davenport 1964) given in Eq. (2),

$$g = \sqrt{2\ln(\upsilon T)} + \frac{0.5772}{\sqrt{2\ln(\upsilon T)}} \qquad (2)$$

where υ is the cycling rate, which is a characteristic frequency representing the width of the spectrum and defined in Eq. (3),

$$\upsilon = \frac{\int_0^\infty f^2 S_u(f) df}{\int_0^\infty S_u(f) df} \quad (3)$$

where f is frequency and $S_u(f)$ is the power spectral density of the longitudinal velocity component. The standard deviation, σ_u, is calculated as in Eq. (4).

$$\sigma_u^2 = \int_0^\infty S_u(f) df \quad (4)$$

In this study, the power spectral density, $S_u(f)$, was obtained from the wind-tunnel measurements, and then by substituting the spectra into the above equations, the peak factor and gust factor were calculated.

Another important parameter that describes the response characteristics of cup anemometers is the distance constant D. A cup anemometer responds to a step change in wind speed exponentially so that it reaches 63% of its final value in a time equal to $\tau = D/\overline{U}$, called the time constant.

3. Wind-tunnel Set-up and Calibration

Three cup anemometers, namely the MK II, Vector A101, and Vaisala WAA151, were calibrated and tested in the boundary-layer wind tunnel at the University of Auckland. The calibration was performed based on the recommendations of ASTM D5096-02 (2017) and using a Pitot-tube sensor as the reference. In addition, the distance constant (D) of each anemometer was determined according to the procedure explained in ASTM D5096-02 (2017). Table 1 summarises the calibration equations and distance constants of the anemometers. In the calibration equations, the measured wind speed (U) is expressed as a function of output pulse rate, f (Hz).

Table 1. Calibration equations and distance constants

Anemometer	**Calibration Eq.**	**Distance constant *D* (m)**
MKII Munro	$U = 0.5012f + 0.3388$	14.26 ± 0.31
Vector A101	$U = 0.0983f + 0.1515$	2.37 ± 0.2
Vaisala WAA151	$U = 0.0965f + 0.2176$	1.27 ± 0.21

An in-house build data logger was used to record the output pulse rates of the Vector and Vaisala anemometers at a sampling frequency of 8 Hz. The AC output voltage of the MK II anemometer was initially converted to pulse outputs and then sampled at a frequency of 4 Hz, due to the low number of pulses per revolution and the variability effects observed at higher sampling frequencies. Different values of turbulence intensities were generated in the wind tunnel by using grids and other roughness elements. In addition, a Cobra sensor, recording the three components of velocity and turbulence, was placed next to the cup anemometers as a reference instrument. In all cases, the mean wind speed was calculated by averaging the wind speeds recorded over a period of 10 minutes.

4. Results and Discussion

Unlike both the Vector and Vaisla cup anemometers, the MK II has heavy cups and consequently higher inertia, resulting in slower response to wind speed fluctuations, and thus measuring lower standard deviations. Figure 2 compares the frequency response of these three anemometers in a turbulent wind with a mean wind speed of 13 m/s and turbulence intensity (I_u) of 14.5%. As can be seen, at low frequencies all the cup anemometers respond quite similarly to the wind speed. However, at high frequencies, the spectra decay faster for anemometers with larger distance constants. The Vector and Vaisala anemometers, because of their similar structure and cup dimensions, show a comparable frequency response at high frequencies, with slight differences.

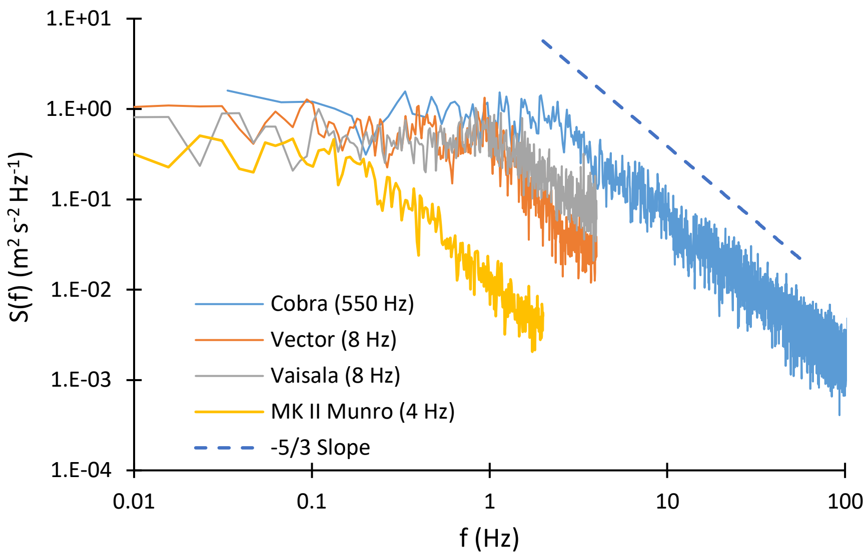

Fig. 2. Comparison of power spectral densities from three cup anemometers and Cobra probe exposed to a turbulent wind field with $I_u = 14.5\%$ and $\overline{U} = 13\ m/s$

In recording and processing gust wind speeds, gust duration plays an important role that can affect the magnitude of the gust wind-speed measurements and other parameters such as the gust factor and peak factor. The effective gust duration before the use of digital recording systems was a function of the anemometer response. However, today the most-accepted definition is an ***equivalent moving average*** (τ_{equiv}) (Holmes et al. 2014). Holmes et al. (2014) showed that for a cup anemometer, τ_{equiv} can be approximated by $2(D/\overline{U})$, and earlier analogue data recorded directly from anemometers had generally an equivalent gust duration of less than 1s, though, since the 1990s, the WMO-recommended 3-s moving average definition has been accepted and adopted by meteorological stations all over the world.

Figure 3 shows how applying moving averages with different durations affects the power spectral density, and filters the original wind speed recorded by the Vector cup anemometer. As can be seen, applying the WMO 3-s moving average filters out a large part of the turbulent wind spectrum, which leads to underestimation of the maximum gust recorded by the instrument.

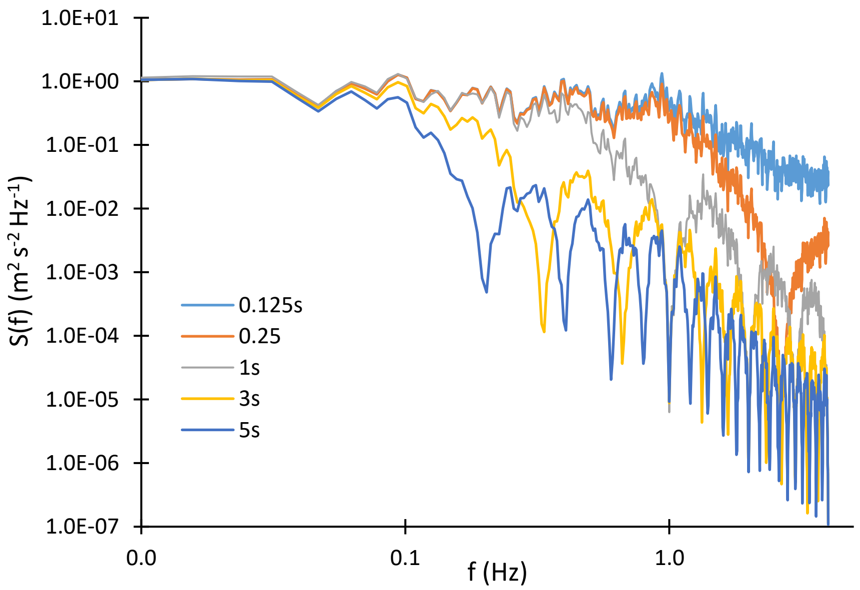

Fig. 3. Effect of applying moving average to the recorded wind speed by Vector A101 at a turbulent wind with $I_u = 14.5\%$ and $\overline{U} = 13\ m/s$

Another effect of applying a moving average filter is a reduction in the area under the wind spectrum and also the width of the spectrum which consequently influences the standard deviation and cycling rate, respectively (Equations 3 and 4). These changes in σ_u and υ cause the peak factor and gust factor to vary with τ_{equiv}. In addition, according to Equation 1, the gust factor is sensitive to I_u, meaning that gust factors vary with the height above ground and terrain roughness. However, peak factors are relatively insensitive to I_u (Holmes et al. 2014). As mentioned above, in this research the wind-tunnel tests were carried out at different I_u, and g and G are calculated for each turbulent condition. Figure 4 shows the variation of g and G with τ_{equiv} for each of the cup anemometers in a turbulent wind with $I_u = 14.5\%$ and $\overline{U} = 13\ m/s$. For other values of I_u, the gust factor ratios are provided in Table 2.

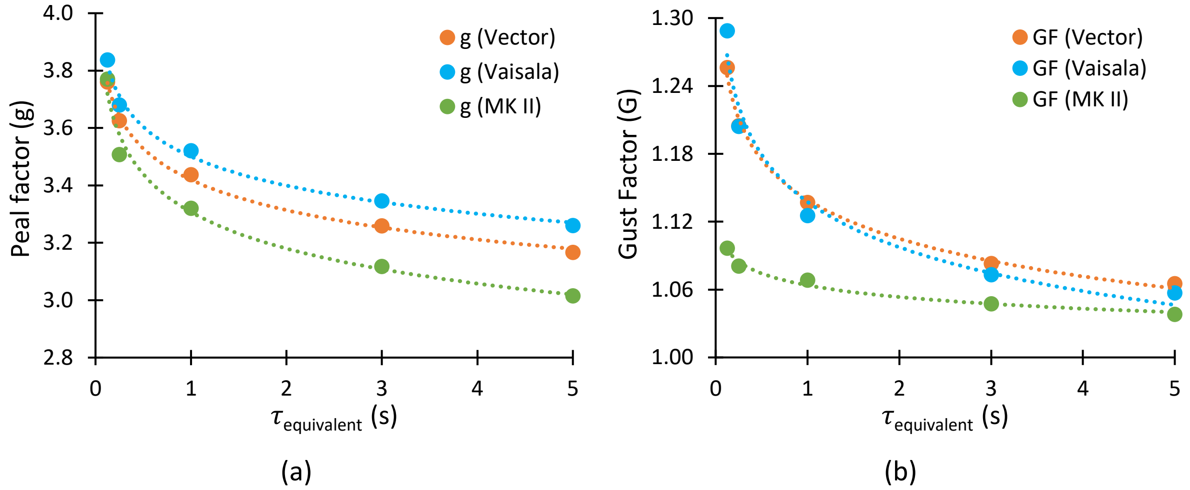

Fig. 4. Effect of applying a moving average to the recorded wind speed on: (a) Peak factor; (b) gust factor

As Figure 4 shows, for shorter gust durations all the tested cup anemometers show a nearly equal peak factor, about 3.7 to 3.8, which agrees with the peak factor of 3.7 reported by Deaves and Harris (1978). However, as the gust duration increases, the peak factors decrease monotonically, with the MK II showing the lowest values at all gust durations. Regarding the gust factor, the Vector and Vaisala anemometers exhibit a similar trend due to their comparable design and recording systems, thus they are quite equally sensitive to wind fluctuations. However, the MK II, due to its heavy cups and slow response to gusts, has much smaller gust factors compared to those of the Vector and Vaisala.

In order to be able to compare the gust speeds recorded in New Zealand by the heavy-duty MK II anemometer prior to 1993 with the new measurements, gust factor ratios between each two of the instruments should be obtained. Here we consider two cases for calculating these gust factor ratios: first, the anemometer response alone, without applying any filter to the output of anemometers; second, 3-s moving average filter was applied to the outputs of the Vector and Vaisala anemometers. The results are summarised in Table 2.

Table 2. Average expected gust factor ratios between pairs of anemometers

		Vector/MK II		**Vaisala/MK II**		**Vector/Vaisala**	
I_u (%)	Mean wind speed (m/s)	Anemometer alone	WMO-3s gust	Anemometer alone	WMO-3s gust	Anemometer alone	WMO-3s gust
8	13.4	1.08	1.02	1.11	1.01	0.97	1.00
8.6	11.3	1.07	1.02	1.10	1.01	0.98	1.00
9.6	4.6	1.08	1.05	1.09	1.03	0.99	1.02
14.3	13.1	1.09	1.03	1.15	1.02	0.93	1.01
15	10.8	1.12	1.03	1.14	1.04	0.96	1.00
16	4.2	1.13	1.06	1.15	1.06	0.98	1.01

In calculating the gust factors for the first case, “anemometer alone”, the gust duration was calculated based on the mean wind speed and the distance constant of each anemometer ($2(D/\overline{U})$). The results show that when comparing the recordings of the anemometers directly, the Vector and Vaisala anemometers record gust values that are 7%-13% and 9-15% higher than those recorded using the MK II, respectively. However, when applying the 3-s moving average filter to the outputs of the Vector and Vaisala anemometers, these differences drop to 2%-6% and 1%-6% for the Vector and Vaisala, respectively. The results of the gust factor ratios can also be interpreted from Figure 4b.

4. Conclusions

In this study, we experimentally assessed the response characteristics of three cup anemometers, namely the Mark II Munro, Vector A101, and Vaisala WAA151 that have been used in New Zealand over the last 40 years, as well as comparing the gust wind speeds measured by these instruments. Random process and linear system theory was used to determine different parameters of the anemometers, and also investigated the effects of applying moving average filters on the wind spectrum, peak factors and gust factors. The results show that on average the Vector and Vaisala anemometers record gust values that are 7%-13% and 9-15% higher than those recorded using the MK II, respectively, and when the WMO-recommended 3-s moving average is applied to the outputs of the Vector and Vaisala, these differences drop to 2%-6% and 1%-6% for the Vector and Vaisala, respectively. More wind-tunnel tests and field measurements are underway to further compare the response characteristics of these anemometers for a wider range of parameters, including turbulence intensity, mean wind speed, and different gust durations and averaging time.

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References

ASTM D5096-02 (2017), "Standard test method for determining the performance of a cup anemometer or propeller anemometer", American Society for Testing and Materials, PA, United States.

Davenport, A.G. (1964), Note on the distribution of the largest value of a random function with application to gust loading. *Proceeding of the Institutions of Civil Engineers*, 28:187-196.

Deaves, D.M., Harris, R.I. (1978), A mathematical model of the structure of strong winds. CIRIA Report 76, Construction Industry Research and Information Association, London, UK.

Holmes, J.D., Allsop, A.C., Ginger, J.D. (2014), Gust durations, gust factors and gust response factors in wind codes and standards. *Wind and Structures*, 19(3):339-352.

Kristensen, L. (1999). The perennial cup anemometer. *Wind Energy*, 2(1):59-75.

Masters, F.J., Vickery, P.J., Bacon, P., Rappaport, E.N. (2010), Towards Objective, Standardized, Intensity Estimates from Surface Wind Speed Observations. *Bull Am Meteorol Soc.* 91, 1665-1681.

Miller, C., Holmes, J.D., Henderson, D., Ginger, J., Morrison, M. (2013), The response of the Dines anemometer to gusts and comparisons with cup anemometers. *J Atmos OceanTechnol*. 30(7):1320-1336.

Safaei Pirooz, A.A., Flay, R.G.J. (2017), Preliminary Extreme Wind Speed Estimates for the Auckland Region. *Proceeding of 9th Asia-Pacific Conference on Wind Engineering,* Auckland, New Zealand, Dec 3-7, 2017 1-4.

Smith, S.G. (1981) Comparison of wind speeds recorded by pressure-tube and Meteorological Office electrical cup generator anemographs. *Meteorological Magazine*, 110:288-300.

World Meteorological Organisation. (2014), "Guide to meteorological instruments and methods of observations", 8th Edition, WMO Publication, Geneva, Switzerland.