Influence of small-scale turbulence on cup anemometer calibrations

M Marraccini1, K Bak-Kristensen1, A Horn2, E Fifield2 and S O Hansen2
1Svend Ole Hansen ApS, Copenhagen, Denmark
2SOH Wind Engineering LLC, Vermont, USA
E-mail: mma@sohansen.dk

Abstract. The paper presents and discusses the calibration results of cup anemometers under different levels of small-scale turbulence. Small-scale turbulence is known to govern the curvature of shear layers around structures and is not related to the traditional under and over speeding of cup anemometers originating from large-scale turbulence components. The paper has shown that the small-scale turbulence has a significant effect on the calibration results obtained for cup anemometers. At 10 m/s the rotational speed seems to change by approx. 0.5% due to different simulations of the small-scale turbulence. The work which this paper is based on, is part of the TrueWind research project, aiming to increase accuracy of mast top-mounted cup anemometer measurements.

1. Introduction

In 2016 the wind energy sector reached 161 GW of installed capacity in Europe, and would, in a normal wind year, produce 352 TWh of electricity enough to cover 12% of the EU’s electricity consumption. A single percent (1%) uncertainty in wind speed estimation due to mal-calibrated cup anemometers results in about 3% uncertainty in the corresponding predicted power production [TWh], due to the cubic law of mechanical energy extracted from the wind by a wind turbine. For the year 2015, a 3% uncertainty in wind power production corresponded on the European scene to about 10.5 TWh. At the present market cost (0.04 Euro per kWh) this 1% uncertainty in wind speed estimation corresponds to more than 400 Millions of Euros.

The calibrations of cup anemometers have been carried out extensively by many wind tunnels starting from the beginning of the 90s. The first calibration deviations were up to approximately 10% of measured wind speed between different wind tunnels. During the last years this band has been narrowed down substantially with deviations of the order of 1%. The uncertainties have been reduced by applying different strategies including the usage of larger wind tunnels and the upgrade of the instrumentation, leading to an increased reliability of the measurements.

A deep and thorough investigation on the characteristics of the flow in the wind tunnel represents, at the moment, the path to follow toward the reduction of the calibration uncertainties. Among the characteristics of the flow in a wind tunnel is the turbulence intensity, which may have an influence on cup anemometer calibrations.

According to Kristensen (1992)[6] a sudden increase of the wind speed gives a torque on the rotor which is numerically larger than a sudden decrease of the same magnitude. Since the...
rotation rate is not in equilibrium with the full-scale turbulent wind, which constantly has many small and fast changes up and down, the rotor will on average tend to run too fast with respect to the mean wind and thus give a positive bias.

Overspeeding in wind tunnels with lower turbulence intensities has been analyzed by Kristensen, Hansen and Hansen (2012)[2]. A turbulence intensity of 1-2% gives a bias of the order of 0.01% to 0.05% indicating that overspeeding is negligible in wind tunnel calibrations at low turbulence intensities.

However the effects of varying small-scale turbulence on cup anemometer calibrations have never been quantified.

The influence of small-scale turbulence on shear layers reattachment has been investigated by Gartshore (1973)[9] and Melbourne (1979)[8]. Tieleman[7] observed that measurements of mean base-pressure coefficients on square-section prisms have a good correlation with the small-scale turbulence (Fig. 1).

![Figure 1: Correlation between mean-base pressure coefficient and small-scale turbulence][7].

Increasing the small-scale turbulence is seen to give numerical smaller suctions on the back side of the structure. For cup anemometer rotors this may affect the forcing both on the driving side and on the resistance side. If the dominating effect of small-scale turbulence occurs on the driving side, the cup anemometer will rotate slower for a specific wind velocity. The cup anemometer will rotate faster if the small-scale turbulence on the resistance side dominates. Thus, whether cup anemometers rotate faster or slower due to small-scale turbulence may depend on the rotor geometry and thereby on the type of cup anemometer considered.

2. Calibration uncertainties

The different uncertainty contributions are illustrated by an uncertainty chain in Fig. 2a and Fig. 2b for the year 2000 and 2015, respectively. The chain gives a picture of the particular conditions relevant for cup anemometer calibrations in Measnet approved wind tunnels. The concept of a chain symbolizes that the total uncertainty is governed by the least reliable of the links. The figure also indicates some interactions between different parts of the chain. For both years 2000 and 2015, the uncertainties associated with the measuring time in the wind tunnel and the reading of the cup anemometer frequency are judged to be minor. The uncertainty originating from the instrumentation has been reduced substantially over the last 10-20 years, and this is illustrated in the figure by a distribution being somewhat narrower in 2015 compared
to 2000. The same tendency is found for the uncertainty due to air flow quality, and this is due to the benefit of having had Measnet requirements concerning flow quality since 1997, e.g. the Measnet requirements of a small horizontal wind velocity gradient in the wind tunnel. The Measnet requirements have forced the approved calibration wind tunnels to improve their flow quality over the years.

![Illustrations of different uncertainty contributions in 2000(a) and in 2015(b).](image)

The uncertainties originating from wind tunnel blockage and tunnel interference are large for small wind tunnels. However, the opening of two Measnet approved very large wind tunnels in Burlington, Vermont, USA, in 2015 has enabled that the uncertainties originating from wind
tunnel blockage and tunnel interference to become negligible in these two wind tunnels. For the two large wind tunnels in Burlington the uncertainties originating from the air flow is not hidden by large uncertainties due to wind tunnel blockage and tunnel interference, and this makes it possible to determine the effect of different air flows on the calibration results without any significant bias from uncertainties originating from wind tunnel size. Thus, the two large wind tunnels in Burlington enable an accurate determination of the effect of small-scale turbulence, and this would have been difficult in smaller wind tunnels because of the dominating uncertainties from other sources.

In spite of good repeatability for a single wind tunnel, different wind tunnels may still have wind speed differences of up to typically 1% between their calibration results obtained for the same cup anemometer, and the differences may depend on the cup anemometer type calibrated. A possible outcome of this is illustrated in Fig. 3.

Figure 3: Bias between wind tunnels Njord 1 (WT1) and Njord 2 (WT2) described by distributions.

The main reason for the systematic bias between wind tunnels may be the influence of blockage and the interference between rotating cup anemometer rotors and tunnel boundaries. The typical Measnet wind tunnel is approx. 1 x 1 m in dimension, and this has turned out to be too small for avoiding blockage and tunnel interference effects that may give biased calibrations using the present procedures. There is a profound need of reference calibrations of different cup anemometers carried out in a larger wind tunnel with cross sectional areas of approx. 5 m$^2$ to 10 m$^2$, where the effect of blockage and tunnel interference are negligible. A comparison between calibrations in smaller and larger wind tunnels may be used to estimate correction factors for the smaller wind tunnels taking into account their blockage and tunnel interference effects thereby reducing the accompanying calibration uncertainties.

It is highly recommended that Measnet initiates a project focusing on these comparisons. The main outcome expected will be reduced uncertainties of calibration results for cup anemometers, and this follows in a natural way the development of reduced uncertainties obtained by Measnet over the last approx. 20 years, see the discussion above.
3. Investigations carried out

3.1. Wind tunnel setup

SOH Wind Engineering LLC, Vermont, USA, owns two large wind tunnels (Njord 1 and Njord 2) with a test section of $2.5 \times 2.5$ m (see Fig. 4). A large amount of cup anemometers of different models and brands are calibrated daily fulfilling IEC\textsuperscript{1} 61400-12-1\textsuperscript{[1]} whose present guidelines does not include the influence of small-scale turbulence. The turbulence intensity of the flow can be manipulated by applying up to two metal screens in front of the contraction. All the experiments carried out for the present work refer to six different turbulence configurations. The two tunnels have been accredited by Measnet\textsuperscript{2} in January 2015 and by IECRE\textsuperscript{3} in April 2017. The approved configuration by Measnet and IEC is without screens. The turbulence requirements are however satisfied for the other screen as well giving a turbulence intensity below 2% which including longitudinal wind speed fluctuations with frequencies of up to 5 Hz.

![Figure 4: Elevation of wind tunnel, SOH Wind Engineering LLC](image)

Different commercial cup anemometers of various models have been calibrated at SOH Wind Engineering LLC under different turbulence conditions. The characteristics of the flow in the calibration point of both tunnels have been measured for different wind velocities through hot-wire anemometers able to measure wind speed fluctuations with a sampling rate up to 10 kHz. Each time series has been used to calculate the power spectral density of the longitudinal velocity component up to 5 kHz according to Nyquist-Shannon theorem. The investigated wind speeds span a range from 4 m/s to 16 m/s, this range being applied for anemometer calibrations according to IEC 61400-12-1.

3.2. Small-scale spectral density parameter

Introduced by Melbourne (1975), the small-scale spectral density parameter $S$ is defined as the spectral density of the longitudinal velocity $nS_u(n)$ ($n$ is the frequency in hertz) at a wavelength $U/n$ corresponding to one tenth of the characteristic length scale $\sqrt{A}$ of the model, normalized by the squared mean wind velocity $U^2$ (Eq. 1).

$$S = \frac{nS_u(n)}{U^2} \quad \frac{U}{n} = 0.1\sqrt{A}$$

Fig. 5 shows the small-scale spectral density parameter at 10 m/s for different configurations. The characteristic length scale $\sqrt{A}$ has been assumed to be 0.13 m. The vertical black line indicates the calculated frequency at 10 m/s.

\textsuperscript{1} International Electrotechnical Commission
\textsuperscript{2} International network for harmonised and recognized measurements in wind energy
\textsuperscript{3} IEC system for certification to standards relating to equipment for use in renewable energy applications
3.3. Anemometer calibration

The calibration expression of a cup anemometer can be rearranged as Eq. 2

\[ f(v_t) = \frac{v_t - k_b}{k_a} \]  

where \( f(v_t) \) is the output frequency of the anemometer at the target wind speed \( v_t \), \( k_a \) is the slope and \( k_b \) is the offset. The comparison is based on the frequency which an anemometer would indicate at a target wind speed \( v_t \).

4. Results

A target wind speed of 10 m/s has been defined and the ideal frequency of each anemometer for each turbulence configuration has been calculated. In order to isolate the dependency on the small-scale turbulence, each anemometer has been analysed independently. This can be achieved by normalising the frequencies corresponding to different experiments (turbulence configurations and different tunnels) by the mean value of all experiments performed on a specific anemometer. This is done in order to investigate the global trend of all the normalized frequencies with respect to the small-scale turbulence as different brands/models of anemometers have different calibration expressions.

The small-scale turbulence parameter can be calculated for a wind speed of 10 m/s based on power spectral density results according to Eq. 1. Fig. 6 shows six vertical bars corresponding to six levels of small-scale turbulence. The normalized frequencies of all anemometers are always contained in the vertical bars. Points where the normalized frequencies are above 1 show that the rotor of the anemometer rotates faster than the average value and vice-versa.

Fig. 6 shows that the investigated cup anemometers rotate slower when the small-scale turbulence is increased. This tendency is found both for cup anemometers rotating clock-wise and anti-clockwise indicating that the change of rotational speed is not caused by non-desired horizontal gradients of the air flow introduced when the screens are installed in the wind tunnels.

The results in Fig. 6 depict a global trend of the averaged frequencies which decrease as the small-scale parameter increases. The \( S \) parameter magnitudes shown in Fig. 1 and Fig. 6

![Small-scale spectral density parameter for 10 m/s and different configurations.](image)
cannot be directly compared as they are calculated for different bodies and under different wind conditions. However the overall trend of the two figures can be compared showing a good correlation between the experiments, assuming that small-scale turbulence dominates the driving side of the rotor.

The absolute deviation of the normalized frequencies between the different turbulence configurations is of the order of 0.5% - 1% whereas small variation of turbulence intensity have been seen to give a bias of the order of 0.01% to 0.05% [2]. The results shown in Fig. 6 cannot be attributed to variations of turbulence intensity indicating that the small-scale turbulence becomes responsible for non-negligible deviations of calibration results.

The wide bars at low levels of small-scale turbulence may originate from different dependencies for different different anemometer brands/models. This evidence can be compared with the results obtained by Tieleman in Fig. 1: lower values of small-scale turbulence correspond to the most inclined sector of the experimental curve, i.e. where small variations of small-scale turbulence can give large differences of mean base-pressure. This is consistent with the observations of the present paper.

5. Conclusions
The paper has shown that the small-scale turbulence has a significant effect on the calibration results obtained for cup anemometers. At 10 m/s the rotational speed seems to change by approx. 0.5% due to different simulations of the small scale turbulence. It is emphasized that the effect of small-scale turbulence originates from changed forcing acting on the rotor, and it is not possible to take this effect into account by the present mathematical models of cup anemometer rotors, e.g. the models applied in cup anemometer IEC classifications [1].

In the short term it is recommended that the Measnet approved calibration wind tunnels quantify their small-scale turbulence, and this information may in the long term lead to requirements for small-scale turbulence in Measnet and subsequently IEC specifications. These requirements may follow Fig. 7b , where full-scale could be a typical full-scale turbulence
condition with normal turbulence. On long term manufactures of cup anemometers may use a small sensitivity to small-scale turbulence as a competitive advantage.

Figure 7: (a) shows a wind tunnel simulation based on a correct representation of the turbulence intensity assumed to be 10%. (b) shows a wind tunnel simulation with reduced turbulence intensity, but a correct representation of the small-scale turbulence. The turbulence intensity in (b) is approx. 2%.

A thorough understanding of all aspects influencing calibrations of cup anemometers is the first step towards increasing the accuracy of wind speed measurements in field. The work presented in the paper regarding the small-scale turbulence influence on the calibrations is a breakthrough in regards to using wind tunnel calibrations results to interpret wind speed field measurements as well as reducing the bias between calibration results obtained in the individual anemometer calibration institutes. This is of great importance in order to meet the demands from the wind energy industry on a reduction of uncertainty regarding the wind speed measurements.

6. Learning objectives
The outcome of the presented work is firstly of great relevance for the anemometer calibration institutes, creating an awareness of the influence of turbulence on the calibration results. The turbulence influence is an aspect well known in other parts of wind tunnel testing experiments but is yet to be recognized within the cup anemometer calibration industry. The present guidelines for cup anemometer calibrations refer alone to the turbulence intensity of the flow not handling the influence of small-scale turbulence and this contributes to the present well known bias between the individual anemometer calibration institutes. The paper aims to spread the achieved knowledge of small-scale turbulence influence for the general benefit of reduction of uncertainties on cup anemometer calibrations.

7. Acknowledgement
The presented work is part of the TrueWind research project, funded by EUDP (Det Energiteknologiske Udviklings og Demonstrationsprogram: a founding program under the Danish Energy Agency).
References

[1] International Standard 61400-12-1, 2017, Second Edition International Electrotechnical Comission (IEC), Geneva, Switzerland.

[2] Kristensen L, Hansen O F and Hansen S O Addendum to: Bias on horizontal meanwind speed and variance caused by turbulence www.windsensor.dk, May 29, 2012

[3] Kristensen L and Hansen O F Bias on horizontal mean-wind speed and variance caused by turbulence www.windsensor.dk, May 27, 2012

[4] Hansen O F, Hansen S O and Kristensen L. Wind tunnel calibration of cup anemometers AWEA Wind Power, Atlanta, 2012.

[5] Dyrbye C and Hansen S O Wind loads on structures Wiley,1997.

[6] Kristensen L The cup anemometer and other exciting instruments Ris National Laboratory, Roskilde, Denmark, April 1992.

[7] Tieleman H W Problems associated with flow modelling procedures for low-rise buildings Journal of Wind Engineering and Industrial Aerodynamics, 1992.

[8] Melbourne W H Turbulence Effects on Maximum Surface Pressures - A Mechanism and Possibility for Reduction Ed. J. E. Cermak, Vol. i, pp. 541-551, 1979, Pergamon Press, New York, N.Y., 1979.

[9] Gartshore I S The effects of freestream turbulence on the drag of rectangular two dimensional prism University of Western Ontario, London, Ontario, Canada, 1973.