Influence of small-scale turbulence on cup anemometer calibrations
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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 shows 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.

Objectives
A single percent (1%) uncertainty in wind speed estimation due to mal-calibrated cup anemometers results in an uncertainty in wind power production correspondent on the European scene, to about 10.5 TWh which at the present market cost (0.04 € per kWh) 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 90’s. 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. The objective of the present work is to quantify the effect of different levels of small-scale turbulence on cup anemometer calibrations.

Methods
SOH Wind Engineering LLC, Vermont, USA, owns two large wind tunnels with a test section of 2.5m x 2.5m. The large test section has contributed to lower the uncertainties due to tunnel blockage and tunnel interference enabling an accurate determination of the effect of small-scale turbulence. This would have been difficult in smaller wind tunnels because of the dominating uncertainties from other sources. Fig.1 shows the test section of the wind tunnels at SOH Wind Engineering compared with a standard Meansest test section of 1m x 1m.

A large amount of cup anemometers of different models and brands are calibrated daily fulfilling IEC61400-12-1, 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 Meansest in January 2015 and by IECRE in April 2017.

The small-scale spectral density parameter $S$ is defined as:

$$ S = \frac{\sigma_s^2}{U^2} $$

where $\sigma_s$ is the longitudinal wind speed power spectral density, $U$ (m/s) is the mean wind speed and $n$ is the frequency. The parameter is calculated for a frequency correspondent to a wavelength of one tenth of the characteristic length scale $\sqrt{A}$.

Fig.2 shows the small-scale spectral density parameter at 10 m/s for different turbulence configurations and the black line indicates the frequency representative of a characteristic length scale assumed to be 0.13 m.

**Fig. 2. Small-scale spectral density parameter for 10 m/s at different configurations.**

Different commercial cup anemometers of various models have been calibrated following the Meansest procedure at SOH Wind Engineering LLC under the six different turbulence configurations. A calibration expression of a cup anemometer can be written as:

$$ f(t) = k_0 f + k_1 $$

and rearranged as:

$$ f(t) = \frac{\nu - k_0}{k_1} $$

where $k_0$ and $k_1$ are respectively the slope and the offset of the anemometer’s calibration expression, $\nu$ is the wind speed and $f$ is the frequency indicated by the instrument. Assuming a target wind speed of 10 m/s, the ideal frequency of each anemometer for each turbulence configuration can be 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.

**Fig. 3. Normalized frequencies as function of the small-scale turbulence parameter $S$ at a target wind speed of 10 m/s.**

The normalized frequencies have been plotted as function of the small-scale turbulence parameter calculated for a wind speed of 10 m/s (Fig.3).

**Fig. 4. Correlation between mean-baseline pressure coefficient and small-scale turbulence (Tieleman, 1992).**

The $S$ parameter magnitudes shown in Fig. 3 and Fig. 4 cannot be directly compared as they are calculated for different bodies and under different wind conditions. The absolute deviation of the normalised 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% (Kristensen, Hansen and Hansen, 2012).

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. In the short term it is recommended that the Meansest 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 Meansest and subsequently IEC specifications. On long term manufacture of cup anemometers may use a small sensitivity to small-scale turbulence as a competitive advantage. This work 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 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.

References
1. International Standard 61400-12-1, International Electrotechnical Commission (IEC) 2017