On cup anemometer performance analysis and improvement: a (still) ongoing process

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Abstract: The cup anemometer, wind speed sensor developed by T.R. Robinson in the 19th century, remains today as the best option in relation to important scientific and economic sectors such as the meteorology sector or the wind energy sector. Despite the great advances reached by new technologies as sonic anemometry, LIDAR or SODAR, the cup anemometer is the most demanded wind speed sensors thanks to its balance between accuracy, reliability, endurance and cost. In the present paper, the work carried out in relation to this instrument at the IDR/UPM Institute is briefly summarized, and then the results from the last research testing campaigns are included. The output signal of first class cup anemometers such as Thies CLIMA First Class, Thies CLIMA 4.3350, and Vector Instruments is analyzed in order to obtain insights on the instrument accuracy. It has been found that the three accelerations of the rotor are translated into a pulsed output signal that could lead to some error if that is not taken into account. Besides, the way the output signal is registered in order to correlate the output frequency with the wind speed has proven to be also a source of error.

***Keywords**: cup anemometer, calibration, MEASNET, wind speed sensor, accuracy*

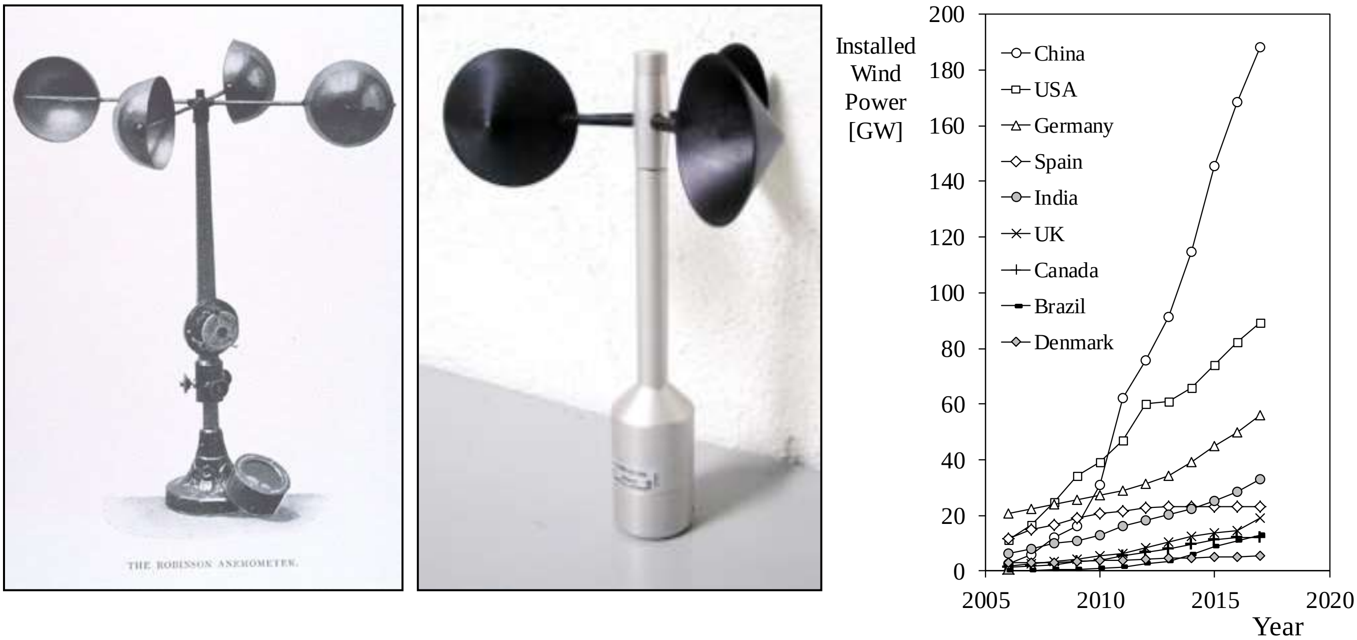
1. INTRODUCTION

Although more (much more) modern wind speed sensors have been developed in the last decades (sonic anemometer, LIDAR, SODAR, nacelle anemometers), the cup anemometer remains as the most popular wind speed sensor in meteorology or the wind energy sector. These scientific activities/economy sectors require quite accurate sensors and the cup anemometer is today the best option thanks to:

- its accuracy, even taking into account the well-known inertia problem effect called overspeeding,
- its reliability and robustness, as these instruments keep on working during long periods in severe outdoor conditions (normally installed at quite high level over the ground),
- its well stablished (and not expensive in relation to other wind speed sensors) calibration processes.

The cup anemometer (Figure 1) was invented by T.R. Robinson in the 19th century. Since then this wind speed sensor has been both experimentally and analytically studied. In the work by Sanz-Andrés et al. [1] there is a thorough literature review on the published research related to this instrument, that review covering the period from the first work published by T.R. Robinson in 1847 to 2013. The evolution of the research on this instrument can be summarized in a few different periods:

- The first one is characterized by the development of the invention by Robinson [2–6], some analytical studies [7,8], and the experimental work by Brazier [9–11].
- After that initial period, in a short time lapse two capital works came out. Patterson defined the best rotor geometry for a cup anemometer, that is, three cups instead of four [12], and Schrenk produced the most influential work in relation to the cup anemometer, defining an analytical model based on the cups' aerodynamics to study the instrument's performance [13].
- A third period starts in the 30's of the 20th century, represented by efforts to better understand the behavior and errors of the cup anemometer [14–20], new analytical models [21,22], and the effect of the wind turbulence [23–27].
- The last period started with the works by Wyngaard et al. [28] and Busch and Kristensen [29], who defined the cup anemometer as a system influenced by different perturbations (horizontal and vertical accelerations of the wind speed), and introduced statistical analysis within the cup anemometer performance modeling.



(a) (b) (c)

Figure 1. (a) Old Robinson cup anemometer, (b) Thies Clima 4.3350 cup anemometer. From [30]. *(c) Installed wind power in the most relevant countries. Source: Global Wind Energy Council.*

According to the world installed wind power (see graph in Figure 1c), it seems that the demand of cup anemometers will continue increasing in the upcoming years. Furthermore, it is possible to assume that this massive demand of cup anemometers (and the associated technical processes such as maintenance and recalibration) has changed from mainly European countries (Denmark, Germany, Spain) to other ones in different continents (China, USA and India). Once the importance of the cup anemometer has been stablished, the authors of the present work find quite surprising to realize that, according to the available literature, the research on this wind sensor seems to have been drastically decreased in the last decade, the main research effort being invested by the international scientific community in other sensors such as the aforementioned LIDAR, SODAR, and nacelle anemometers. Nevertheless, it is fair to say that some research on cup anemometers has been published:

- The work by Bégin-Drolet et al. in 2013 [31] should be mentioned first, as the last published work devoted to filter a cup anemometer output signal in order to improve wind turbulence measurement. This work represents a worthy contribution in the line of work of other authors such as Torochkov and Surazhskiy [32], Hayashi [33], Hristov et al. [34], Solov'ev et al. [35], Selyaninov [36], and Yahaya and Frangi [37].
- Some effort has been carried out to simulate the cup anemometer performance with Computational Fluid Dynamics [38–41].

- Finally, the effort in the last years seems to be focused on the progressive lack of accuracy due to the anemometer wear and tear that might compromise the wind turbines' optimal energy production [42–50].

According to the work performed at the IDR/UPM institute [1,51–61], the authors believe that there is still room for improving the cup anemometer and its accuracy. This improvement might come from:

- new analytical models,
- better output signal generators,
- more efficient rotors in terms of aerodynamics, and
- output signal processing, that could filter effects as the three rotor accelerations per turn due to the cups, and the inertia effects (overspeeding).

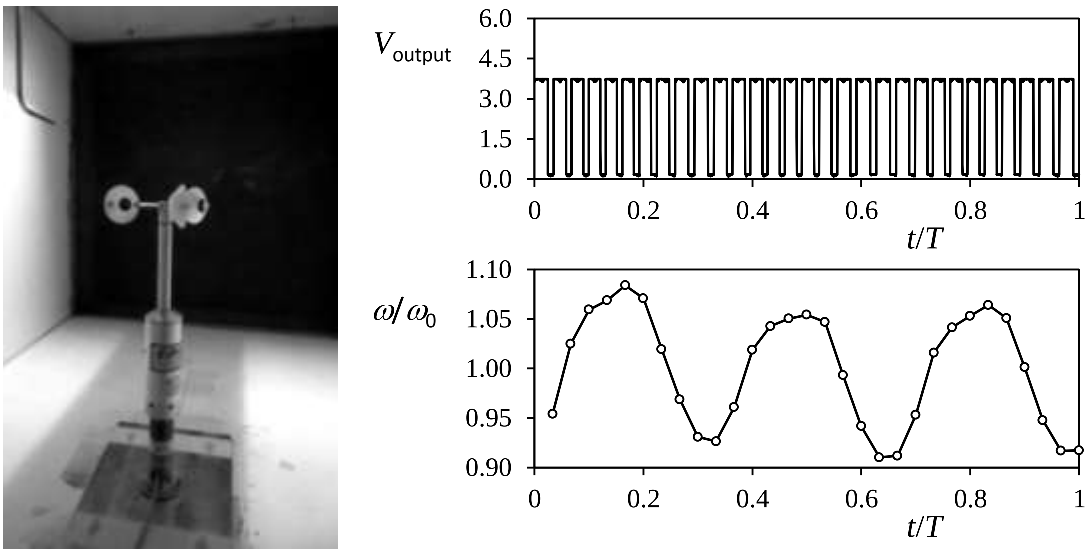
The last research works carried out in the IDR/UPM Institute on the cup anemometer are summarized in the present work. This works focus on the cup anemometer's output signal and how the way it is recorded by the dataloggers can affect the measurements of the wind speed. The present paper is organized as follows. In Section 2, the most important characteristics of the cup anemometer performance and the way this instrument is calibrated are described. The results obtained by the authors are included in Section 3. Finally, conclusions are summarized in Section 4.

2. CUP ANEMOMETER PERFORMANCE AND CALIBRATION PROCEDURE

Despite some isolated result [62], the cup anemometer is an instrument whose transfer function is accepted to be linear, that is, the measured wind speed, *V*, depends linearly on the output frequency of the generated signal, *f*::

$$V = \mathrm{A}\, f + \mathrm{B}, \quad (1)$$

where A (slope) and B (offset) are constants that should be defined by a proper calibration process [63–66]. The cup anemometer calibrations performed at the IDR/UPM Institute follow MEASMET protocols strictly, the LAC-IDR/UPM lab being ISO 17025 standard accredited [67]. More information can be found at [51]. Concerning the output signal of this wind sensor, the most accurate and popular cup anemometers within the wind energy sector are those that give from 25 to 37 squared pulses per turn. That has led us to study this output signal using Fourier analysis (see Figure 2).



(a) *(b), (c)*

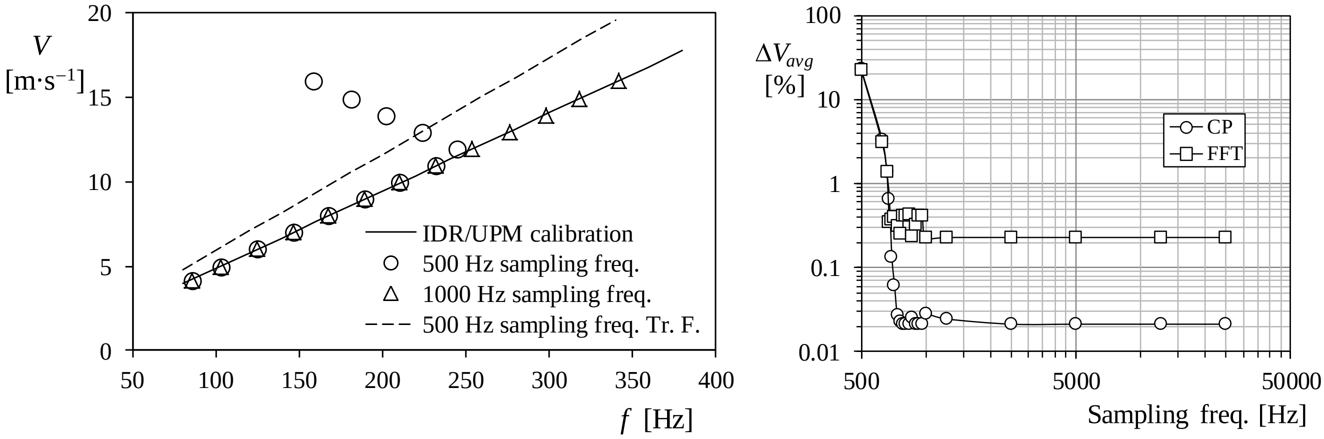
Figure 2. (a) Cup anemometer being calibrated at the IDR/UPM Institute wind tunnel, (b) Train of pulses (voltage signal, V_{output}) along one turn, (c) Variations of the rotor speed rate in relation to the average rotation rate, ω/ω_0, along one turn. From [61].

3. RESULTS

The study of cup anemometers output signal by means of Fourier analysis has helped to identify clearly the need of maintenance of a cup anemometer, as the problems such as one broken cup, dirt accumulation, bearings malfunction…, are usually reflected in the first harmonic term of the rotation rate along one turn (these problems are translated into a one single perturbation within each rotation) [59]. Besides, the effect of the three accelerations of the rotor (Figure 2c) on a calibration process has been analyzed. This is translated into a certain loss of accuracy if not complete turns of the rotor are taken into account within the calibration process [68]. Fortunately, this lack of accuracy can be greatly alleviated if a sufficiently large number of output pulses are measured for each wind speed. The last research campaign at the IDR/UPM Institute was focus on a benchmark between:

- calibrations performed by using counting pulses (CP) as the way of measuring the cup anemometer output frequency, and
- calibrations performed by using the Fast Fourier Transform (FFT) to measure this output frequency.

The purpose of this research campaign is to give some information on the accuracy of using the FFT to measure the cup anemometer's output frequency, as some labs might use this technique instead of counting pulses. The first (and obvious) conclusion of this research was that the accuracy of the calibration results depends on the sampling frequency. In Figure 3a, the calibration points obtained from 25-seconds large datasets at 500 and 1000 Hz sampling rates. As it can be observed in the figure, not enough high sampling rates limits the possibility of calculating the cup anemometer output frequency properly. The second conclusion was that once the size of the sampling dataset is large enough (around 15 s), and the sampling frequency is high enough, the errors are stabilized, and the CP method shows a smaller error. In Figure 3b, the averaged difference between of two types of calibrations (obtained by CP and FFT) and the velocities from a proper calibration are shown in relation to the later ones, as a function of the sampling rate. The better accuracy shown by counting pulses is clear.



(a) (b)

Figure 3. (a) Points (output frequencies) calculated with 500 and 1000 Hz sampling frequency 25-second large datasets. The transfer function based on the points calculated with 500 Hz sampling frequency dataset and the proper calibration of the cup anemometer are also included, (b) Averaged value of the transfer function error of calibrations performed by calculating the anemometer output frequency using CT and FFT.

4. CONCLUSIONS

The accuracy of cup anemometers can be increased by better analyzing their output signal. Despite the apparent lack of interest on this instrument among the scientific community in the last years, there is still room for improvement.

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