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Research Article

Performance Analysis of Present Cup Anemometers

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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 sensor thanks to its balance between the accuracy, reliability, endurance and the 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 the first class cup anemometers such as Thies CLIMA First Class, Thies CLIMA 4.3350, and Vector Instruments is analyzed to obtain insights on the instrument accuracy. It is found that three accelerations of the rotor are converted into a pulsed output signals, leading 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. Two ways of extracting the output frequency, namely by Counting Pulses (CP), and by using FFT are compared. Results indicate that the wind speed errors are six times larger in the case of using FFT.

***Keywords**:* *Accuracy, Calibration, Cup anemometer, MEASNET, Wind speed sensor*

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1. INTRODUCTION

Although many modern wind speed sensors (i.e. sonic anemometer, LIDAR, SODAR, nacelle anemometers) have been developed in the last decades, the cup anemometer remains as the most popular wind speed sensor in meteorology or the wind energy sector. These scientific activities or economy sectors require accurate wind speed sensors, and the cup anemometer being the best option thank to the followings:

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

The cup anemometer was invented by T.R. Robinson in the 19th century (see Figure 1(a-c)). Since then this wind speed sensor has been both experimentally and analytically studied in many papers. In the work by Sanz-Andrés *et al.*, there is a thorough literature review on the published research related to this instrument [1]. This review covers the studies for more than 150 years, from the first work published by T.R. Robinson in 1847 to 2013. The evolution of the research carried out 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 this initial period, two capital works came out in a short time lapse. 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 aerodynamics of cups to study the performances [13]. The 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.

According to the world installed wind power (see graph in Figure 1(c)), 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).

The importance of having the most possible accurate wind sensors led national and international agencies to develop codes of practice, regarding the calibration of these instruments (and the definitions of the uncertainties in relation to this procedure), and their use (installation in met-masts, or on wind turbine nacelles) [30,31]. Additionally, the work carried out by MEASNET (Measuring Network of Wind Energy Institutes) should be underlined. This cluster of accredited labs have developed a very well-known calibration process of wind sensors, with standardized criteria [32,33].

Once the importance of the cup anemometer has been stablished, it is quite surprising to realize that according to the available literature, the research on this wind sensor seems to have been drastically decreased within the last decade. As the main effort on research by the international scientific community has been driven towards the development of sensors based on much modern technologies such as LIDAR, SODAR, and nacelle anemometers, less and less interest in cup anemometer improvement has been taken by the research community. Nevertheless, it is fair to say that some interesting research on cup anemometers has been published in the last years. The work by Bégin-Drolet *et al.* in 2013 [34] 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 [35], Hayashi [36], Hristov *et al.* [37], Solov'ev *et al.* [38], Selyaninov [39], and Yahaya and Frangi [40]. Besides, some effort has been carried out to simulate the cup anemometer performance with Computational Fluid Dynamics [41-44]. 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 turbine optimal energy production [45-53].

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

Figure 1. (a) Old Robinson cup anemometer, (b) Thies Clima 4.3350 cup anemometer. From [54]. *(c) Installed wind power in the most relevant countries. Source: Global Wind Energy Council*

According to the work performed at the IDR/UPM institute [1,55-65], the authors believe that there is still room for improving the cup anemometer design 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 such as the three rotor accelerations per turn due to the cups, and the inertia problems (overspeeding).

The last research work carried out at the IDR/UPM Institute on cup anemometer performances is summarized in the present work. This work is focused on the output signal of cup anemometers, and how the way this signal is recorded by the data-loggers can affect the measurements of the wind speed. Additionally, the output signal of a cup anemometer was analyzed in order to detect the errors of the mechanical parts comprised by the output signal generator that creates the squared wave output signal. These errors, called the signature, constitute a unique information from each individual anemometer that might reveal problems in the manufacturing, and its definition could help to improve the instrument accuracy if they are properly taken into account by the measurement system.

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

Despite some isolated results [66], 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* (see Figure 2):

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

where A (slope) and B (offset) are constants that should be defined by a proper calibration process [31-33,67]. The cup anemometer calibrations performed at the IDR/UPM Institute follow MEASMET protocols strictly, the LAC-IDR/UPM lab being ISO 17025 standard accredited [68]. More information can be found at [55].

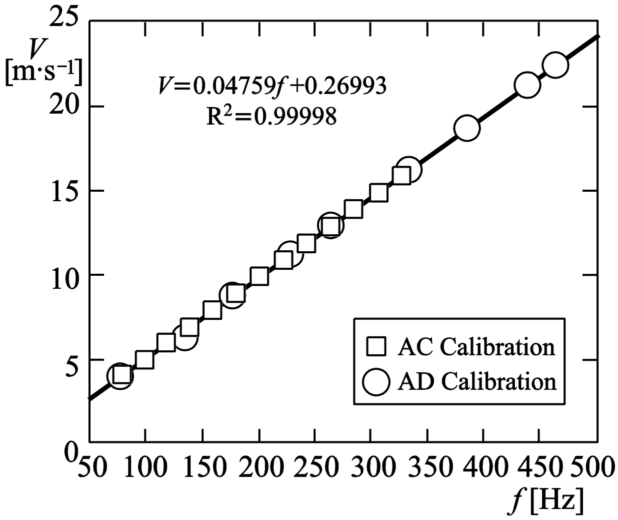


Figure 2. Data from two calibrations (AC and AD calibrations) performed on a Thies 4.3350 cup anemometer. The wind speed, V, is plotted in relation to the anemometer frequency output, f. The regression line corresponding to the AC calibration is displayed in the insert. From [55]

Concerning the output signal of this wind sensor, there are two main possibilities with regard to the system that generates it: Rotating magnets (sinusoidal output wave) and optoelectronic systems. The last ones are the most popular between the top-accurate cup anemometers. In Figure 3, the opto-electronic system of a Climatronics 10075 cup anemometer is shown. The output signal generated is, as said, a square wave in which the higher voltage level corresponds to the moment when a slot of the wheel (see Figure 3) lets the light generated by a led pass through it and, consequently, a light sensor located at the other side of the wheel is illuminated. Obviously, when the sensor is not illuminated the voltage of the signal drops to zero (see in Figure 4). A train of pulses are generated by this signal along one turn of the rotor of cup anemometer.

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 implies a quite good definition of the accelerations of the rotor along one turn, which has led us to study this output signal by using Fourier analysis (see Figure 4).

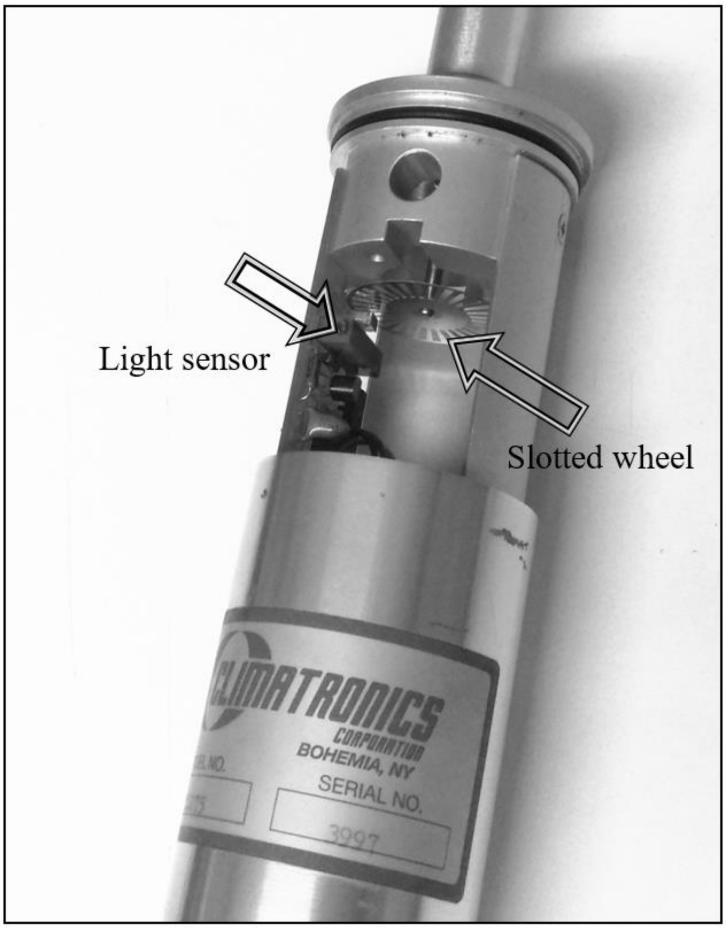
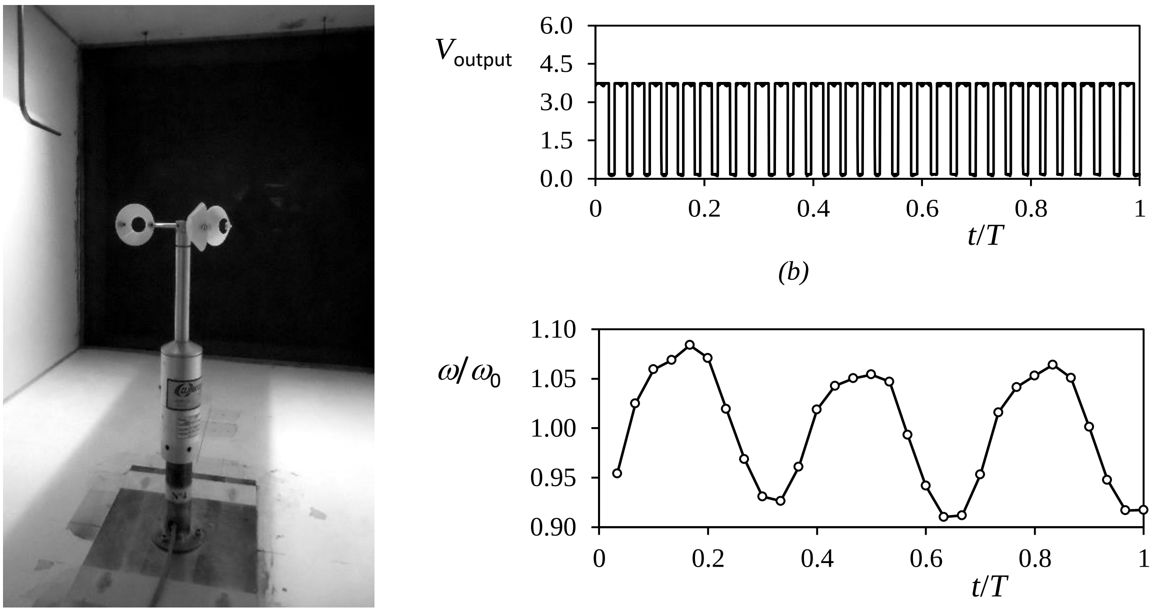


Figure 3. Optoelectronic output signal generator system of a cup anemometer



(a) (c)

Figure 4. (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 along one turn. From Ref. [63]

3. RESULTS

The study of cup anemometers output signal by means of Fourier analysis has helped us to identify clearly the need of maintenance of a cup anemometer. Problems such as one broken cup, dirt accumulation, bearings malfunction, etc., 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) [61]. Besides, the effect of the three accelerations of the rotor (Figure 4) on a calibration process has been also 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 [69]. 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 campaigns at the IDR/UPM Institute were focused on a benchmark between the 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 (CP). A proper calibration of a cup anemometer, based on MEASNET procedures, requires 13 measurement points taken between 4 $m \cdot s^{-1}$ and 16 $m \cdot s^{-1}$ and define the transfer function of the wind sensor (that is, the constants A and B from Eq. [1]). Obviously, the accuracy of the calibration results will depend on the sampling frequency, firstly. Figure 5 shows the calibration points of a Thies First Class cup anemometer obtained from 25-seconds large datasets at 500 and 1000 Hz sampling rates. It is clear from the figure that a not enough high sampling rate limits the possibility of calculating the cup anemometer output frequency, introducing errors that will greatly affect the transfer function of the cup anemometer.

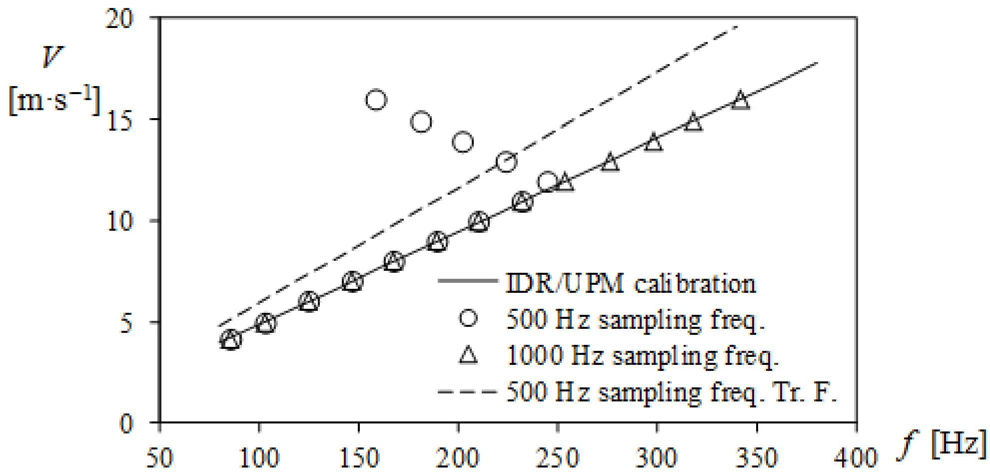


Figure 5. Points (output frequencies) calculated with 500 and 1000 Hz sampling frequency 25-second large datasets obtained from the calibration of a Thies First Class cup anemometer. The transfer function based on the points calculated with 500 Hz sampling frequency dataset is included as a dashed line. From [70]

Five Thies First Class cup anemometers were analyzed in this research campaign. The different cases (sampling frequencies, length of the datasets, etc.) studied are included in Table 1. The mean percentage error from calibrations (13 points, constants A and B) of one of these anemometers in relation to the proper calibration obtained with the ISO/IEC 17025 accredited system of the IDR/UPM Institute (constants A* and B*):

$$\Delta V_{avg} = \frac{1}{13}\sum_{i=1}^{13}\frac{\left|\left(A^* f_i + B^*\right) - \left(A\, f_i + B\right)\right|}{\left(A^* f_i + B^*\right)}, \qquad (2)$$

is shown in Figure 6. In this figure, the errors from calibrations obtained from 25-second datasets by CP and FFT, are compared with regard to the sampling frequency. The results indicate a more accurate calibration if CP is used instead of FFT. Besides, this better behavior of the CP procedure to extract the cup anemometer output frequency was proven to be better than FFT no matter the length of the dataset used as a source.

Table 1. Cases analyzed in the Benchmark between CP and FFT

Anemometers calibrated	Anemometer-1 Anemometer-2 Anemometer-3 Anemometer-4 Anemometer-5	
Points per calibration	4 m 5 m s^{-1} 6 m s^{-1} 7 m s^{-1} 8 m s^{-1} 9 m s^{-1} 10 m s^{-1}	11 m·s^{-1} 12 m·s^{-1} 13 m·s^{-1} 14 m·s^{-1} 15 m·s^{-1} 16 m·s^{-1}
Length of samples	5 s 10 s 15 s 20 s	
Sampling frequencies analyzed	500 Hz 625 Hz 657.89 Hz 675.98 Hz 694.44 Hz 714.29 Hz 735.29 Hz 757.58 Hz 781.25 Hz 806.45 Hz	833.33 Hz 862.07 Hz 892.86 Hz 925.93 Hz 961.54 Hz 1000 Hz 1250 Hz 5000 Hz 12500 Hz 25000 Hz
Calculation of the output frequency, *f*	CP (Counting Pulses) FFT	

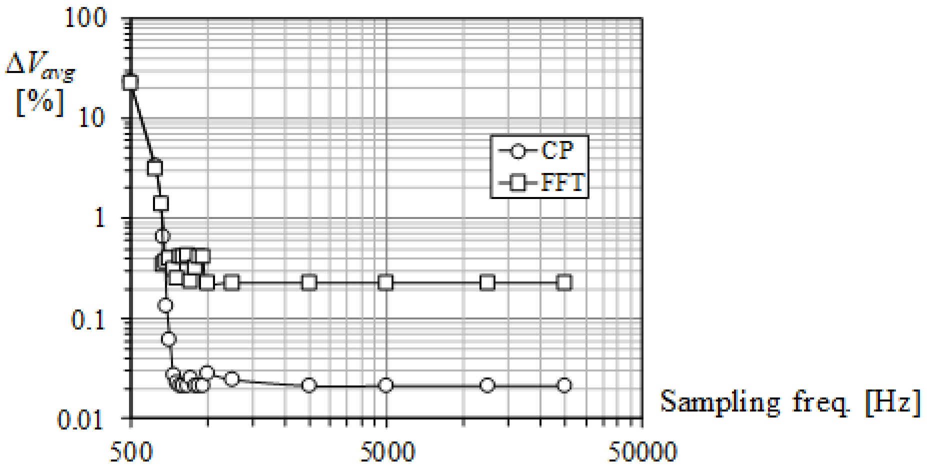


Figure 6. Averaged value of the transfer functions wind speed error, ΔV_{avg}, in relation to the sampling frequency. The residuals were calculated by CP and by using FFT. From [70]

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 if this fact is taken into account properly.

The most relevant conclusion of the research carried out is that the calculation of the cup anemometer's sampling frequency is simple but highly relevant: The better procedure is to carry out this calculation by counting pulses (CP) instead of using the Fast Fourier Transform (FFT). The results of the present work indicate wind speed errors six times larger when using FFT than the errors obtained by CP.

However, last results obtained at the IDR/UPM Institute suggest that FFT is a more robust procedure in case of problems at the sensor's opto-electronic output system (for example is ono or more pulses are lost due to accumulation of dirt at the slotted wheel).

Therefore, a combination of both when a cup anemometer is working on the field might be a good strategy to detect failures on the aforementioned opto-electronic output system.

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