Measurement 90 (2016) 483–490

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Deviations of cup anemometer rotational speed measurements due to steady state harmonic accelerations of the rotor

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ARTICLE INFO

Article history:
Received 3 November 2015
Received in revised form 28 April 2016
Accepted 5 May 2016
Available online 6 May 2016

Keywords:
Cup anemometer
Wind speed measurements
Fourier analysis

ABSTRACT

The measurement deviations of cup anemometers are studied by analyzing the rotational speed of the rotor at steady state (constant wind speed). The differences of the measured rotational speed with respect to the averaged one based on complete turns of the rotor are produced by the harmonic terms of the rotational speed. Cup anemometer sampling periods include a certain number of complete turns of the rotor, plus one incomplete turn, the residuals from the harmonic terms integration within that incomplete turn (as part of the averaging process) being responsible for the mentioned deviations. The errors on the rotational speed due to the harmonic terms are studied analytically and then experimentally, with data from more than 500 calibrations performed on commercial anemometers.

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1. Introduction

The cup anemometer, invented in the XIX century by T.R. Robinson, remains today the most popular wind speed sensor, even taking into account the great development carried out on more sophisticated instruments such as the sonic anemometer, the Lidar, and the Sodar [1]. The performances of this instrument have been thoroughly studied since the XIX century (a quite complete review of the literature on this wind sensor can be found in [2]). As a consequence, different sources of error have been identified in relation to cup anemometer wind speed measurements: turbulence [3–6], non-linearity of the sensor performance [7,8], and the sampling method [9]. Additionally, it should be underlined that uncertainties associated to cup anemometer wind speed measurements have been widely studied, as they are relevant for wind turbines performances [10–12]. According to Eecen and De Noord [13], ISO specifies "two types of uncertainties: category A, the magnitude of which can be deduced from measurements, and category B, which are estimated by other means." The second category, B, takes into account uncertainties related to the anemometer calibration process, such as: wind tunnel correction and calibration; pressure transducer sensitivity and signal conditioning gain; ambient temperature transducer; temperature signal conditioning gain and digital conversion; Pitot tube head coefficient; barometer's sensitivity, signal conditioning gain and signal digital conversion; humidity correction; and statistical uncertainty associated to the mean of wind speed time series. The reported uncertainty levels by these authors at 10 m/s wind speed were 0.26–0.63% (type A) and 0.3–0.7% (type B).

After a review of the available literature, it can be said that not much effort has been carried out to analyze the cup anemometer errors due to sampling. On the contrary, it seems that the errors related to angular speed sampling on other rotating instruments such as tachometers and speed regulators have been quite deeply studied [14–19]. These instruments normally involve a mechanical design that gives several pulses per turn of the shaft. When measuring the angular speed of a shaft, it is possible to count pulses within a period, to measure the time between two consecutive pulses, or combinations of these two methods [16,17,20]. Regarding the sampling process, some authors suggest to establish the sampling period as a function of the pulse output frequency [14], other authors have suggested the detection of the angular speed averaging the measurement during one turn [19].

A difference between cup anemometer output signal generators and industrial tachometers is the number of pulses per turn. Industrial tachometers give normally a quite high number of pulses per turn (from 290 [17], 720 [15], or 1024 [16] pulses, to 25,000 pulses thanks to integral electronic interpolation over the measurements on a 5000-pulse system [18]), whereas the number of pulses given by cup anemometer is much smaller (from 1 to 44 [21]).

Besides, a specific effect related to cup anemometer performance is its non-constant rotational speed, as a result of the 3-cup configuration that produces three accelerations per turn.

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http://dx.doi.org/10.1016/j.measurement.2016.05.011
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Even in an absolute laminar and steady flow, a cup anemometer rotation speed has not a constant value. In Fig. 1, a relative-to-the-average rotation speed, ω/ω_0, is plotted during one turn. This rotation speed corresponds to the signature of a Thies 4.3303 anemometer measured at 8 m/s wind speed [22]. It can be noted in this figure the aforementioned three accelerations. Considering this speed periodic, it can be expressed in terms of a Fourier expansion:

$$\omega(t) = \omega_0 + \sum_{n=1}^{\infty} \omega_n \sin(n\omega_0 t + \varphi_n), \quad (1)$$

the coefficients corresponding to $n = 3$ and its multiples being the most relevant. See in Table 1 the harmonic terms, ω_n/ω_0, corresponding to the Fourier expansion applied to the data from Fig. 1. See also in Fig. 1 the quite exact approximation to the results given by a 6-harmonic term Fourier series.

However, it should be also pointed out that the 44-pulse per turn output signal system of the Thies 4.3303 anemometer has a certain degree of imperfection, that is, there are up to 10% length differences between pulses measured at a strictly constant rotational speed (i.e., up to 10% length differences between the different teeth of the opto-electronic system's rotating wheel) [22]. In Fig. 2, the relative-to-the-average rotation speed, ω/ω_0, based on the signal given by the opto-electronic output system of the anemometer is plotted. This signature needs to be properly corrected to reach the signature of Fig. 1, this correction being done adjusting each pulse of the turn to the exact length of its corresponding tooth of the opto-electronic system's rotating wheel. In Fig. 2, the 6-harmonic and 3-harmonic terms Fourier expansions applied to the signal are also included. The coefficients of the Fourier series expansion of this uncorrected signature are also included in Table 1. Obviously, greater values are obtained as the mechanical differences between the pulses add a noise pattern to the signature that is repeated every turn of the rotor. Nevertheless, the relative importance of the first and third harmonic terms remains in the Fourier expansion related to the uncorrected signature. In addition, it can be observed in Fig. 2 that the 3-harmonic term Fourier expansion reasonably approaches the corrected rotation speed of the anemometer (represented in the figure by the 6-harmonic term Fourier expansion from Fig. 1).

Even with the problems related to the mechanical differences between pulses of the signal generators, this Fourier expansion has been successfully applied to study cup anemometers and detect anomalies on their performance [23–25]. In the present work the Fourier expansion of the measured rotation speed is used to analyze the effect of the sampling process, which is normally based on fixed periods of time (in general between 1 s and 10 min), programmed on the data-loggers connected to anemometers working on the field.

Table 1
Fourier expansion coefficients, i.e., harmonic terms from Eq. (1), related to the corrected and un corrected signatures of a Thies 4.3303 anemometer measured at 8 m/s wind speed [22], see also Figs. 1 and 2.

Corrected signature			Uncorrected signature		
n	ω_n/ω_0 (%)	φ_n (°)	n	ω_n/ω_0 (%)	φ_n (°)
1	0.103	−103.92	1	0.310	2.24
2	0.034	−7.76	2	0.152	−47.63
3	0.785	126.14	3	1.187	108.06
4	0.014	28.81	4	0.114	−100.23
5	0.026	−108.88	5	0.468	48.86
6	0.165	−78.58	6	0.326	−85.62
7	0.017	−93.96	7	0.221	37.34
8	0.008	80.81	8	0.102	175.92
9	0.052	121.68	9	0.688	40.28
10	0.011	110.74	10	0.066	3.95
11	0.018	37.31	11	0.585	10.52
12	0.027	8.85	12	0.135	−72.33
13	0.011	−144.03	13	0.428	9.40
14	0.008	−54.78	14	0.358	−67.69
15	0.015	−15.17	15	0.636	−29.79
16	0.013	26.01	16	0.193	−55.31
17	0.010	174.73	17	0.494	−31.54
18	0.016	−134.93	18	0.173	54.57

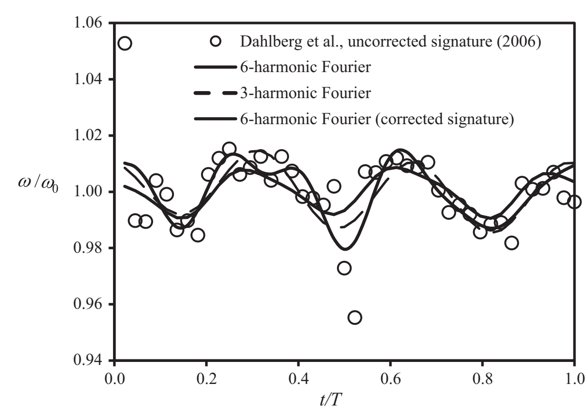

Fig. 2. Measured cup anemometer's non-dimensional rotational speed, ω/ω_0, along one turn of the rotor. This rotation speed is the uncorrected signature of a Thies 4.3303 anemometer measured at 8 m/s wind speed [22]. The corresponding 6-harmonic and 3-harmonic terms Fourier series expansion has been added to the graph. Also, the 6-harmonic terms Fourier series expansion related to the corrected signature (Fig. 1) is included in the graph.

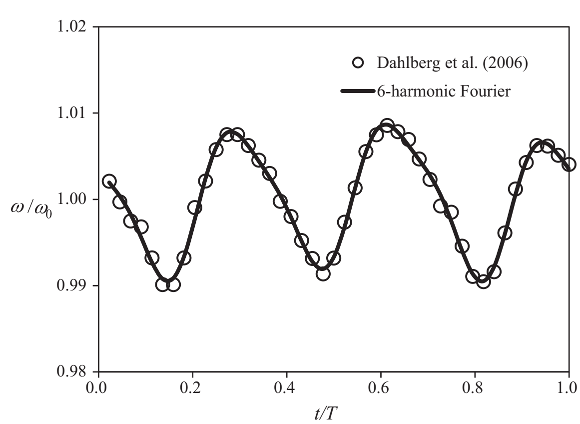

Fig. 1. Cup anemometer's non-dimensional rotational speed, ω/ω_0, along one turn of the rotor. This rotation speed is the corrected signature of a Thies 4.3303 anemometer measured at 8 m/s wind speed [22] (the uncorrected signature of the anemometer is shown in Fig. 2). The corresponding 6-harmonic terms Fourier series expansion has been added to the graph.

The aim of the present paper is to study the effect of the sampling period on the mean wind speed measurements, by taking into account the rotor accelerations of the anemometer (i.e., the changes of the rotation speed) along one turn. As the measured wind speed and the rotational frequency are linearly correlated (at normal wind speed ranges, see MEASNET procedures [26]), the present work has been focused on the rotational speed.

2. Cup anemometer's rotation speed sampling period

In Fig. 3 the rotation speed from Fig. 1 has been extrapolated along an hypothetical measurement period, T_d, equal to three rotation periods, T, plus an extra time t' ($t' < T$). Therefore, for a given measurement period, T_d, equal to m rotation periods plus an extra time t', that is, $T_d = mT + t'$, the mean rotation speed can be calculated as:

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