Fragments of the Cup Anemometer History

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The cup anemometer was invented in 1846 by the Irish astronomer Thomas R. Robinson. An interesting account of its history, including forerunners, has been given by Middleton (1969). The first anemometers had four cups. This is reflected in the fact that in German the instrument is known as the “Schalenkreuzanemometer”. Also in Danish it is sometimes called “skålkorsanemometer”. The building blocks in these languages are “Schale”=“skål”=“bowl”/“cup” and “Kreuz”=“kors”=“cross”, and the last part of the word indicates that the cup anemometer has four arms. Robinson believed that, provided friction in the bearing can be neglected, a law of nature implied that the speed of the center of the cup was exactly one third of the wind speed. The wind speed divided by the speed of the cup was called *the factor*. Although this is not too far from reality, it is by no means true. However, it reflects the remarkable linearity of the calibration, even for the first versions of the instruments.

A thorough investigation of the cup anemometer by Patterson (1926) revealed that the factor varied between 2 and 3. In fact, he found that it varied not only from instrument to instrument, but also as a function of wind speed for a single instrument, albeit to a lesser degree. This of course means that the calibration cannot be completely linear. His work showed that the linearity is better the larger the ratio of the cup radius to the arm length. Another conclusion from his work was that anemometers with three cups is better than cup with four cups because they respond more readily to changes in wind speed.

In the 1920th the cup-anemometer development had led to an instrument with a calibration which had a calibration which, for all practical purposes, could be considered linear. However, it was noticed that in turbulent wind, the output signal was larger for a particular mean-wind speed than the output from the same instrument exposed to a constant wind speed of the same magnitude in a wind tunnel. This phenomenon was called *overspeeding* and it was ascribed to the asymmetric response to changes in the wind speed: for a cup anemometer to work at all, it must respond more readily to an increase than to a decrease in the wind speed (Kristensen 1993, Kristensen 1999). As a consequence, the time spent above the mean wind becomes larger than the time spent below, with the result that the mean-wind measurement will be to large. To analyze the overspeeding it was necessary to understand the dynamics, i.e. the equation of motion, of the cup anemometer. Schrenk (1929) was, according to Wyngaard (1981), the first to publish a systematic attempt to model the dynamics of the motion of the cup-anemometer rotor. From the point of view that it is not possible to describe the detailed air-flow patterns around a moving cup rotor, this model captured the asymmetry by assigning a larger drag coefficient to the concave than to the convex side of the cup. Much effort was invested in the exploitation of this model to understand overspeeding. No definite conclusion was obtained for four decades. Then Wyngaard et al. (1974) decided to set up a pragmatic, phenomenological model for the equation of motion and for the various wind contributions to the torque on the cup rotor. These contributions were measured in a wind tunnel. The new data were interpreted independently by Kaganov & Yaglom (1976) and Busch & Kristensen (1976). They came to the same quantitative result for the effect of the asymmetric rotor response. It had to result in a positive bias of the wind speed in a turbulent wind. Both Kaganov & Yaglom (1976) and Wyngaard (1981) have given interesting accounts of the history of overspeeding.

It is generally believed that the overspeeding is entirely due to the asymmetric response. It is true that a slow cup anemometer with a large moment of inertia of the cup rotor overspeeds more than a light and small anemometer with a small moment of inertia. However, a more detailed analysis (Kristensen 1993, Kristensen 1998) shows that in general there are more important contributions to the mean-wind bias one gets in turbulent winds. The most important are related to the fluctuations in the lateral and the vertical velocity components. These biases are both proportional to the corresponding variances, which must be known to correct the mean wind. Further, it is necessary to know the angular response. This has recently been obtained for the Risø P2546A model and four other commercially available anemometers, Vector A10K, Climatronics F460, Max40, and MetOne (Papadopoulos et al. 2001). The ideal angular response is the so-called *cosine response*, which means that the anemometer is sensitive only to the wind component perpendicular to the rotor shaft. If the angular response falls below the cosine response, the anemometer will actually *underspeed*. There are also contributions to the bias from the covariance between the vertical and the streamwise components, calibration non-linearity (Kristensen 2002), and from signal processing (sample-and-hold)(Kristensen et al. 2003), but they are small and seldom of practical importance.

According to (Kristensen 1993, Kristensen 1998) the calibration of the cup anemometer can be characterized by a *calibration distance* ℓ and a *starting speed* $U_\circ$. The rate of rotation S (in rad/s) at a particular wind speed U is then

$$S = \frac{U - U_\circ}{\ell}.$$

Usually $U_\circ$ is only of the order 0.1 m/s so that at wind speeds much larger than $U_\circ$, ℓ can be interpreted as the length of the column of air which has to pass through the anemometer for the rotor to turn one radian. It should be emphasized that the calibration is a *geometric* property in the sense that it is independent of the density of the cup-rotor material. This is not the case for the *distance constant* $\ell_\circ$, which characterizes the dynamic response. This length is proportional to the linear dimensions of the rotor and to the ratio of its density to that of air (which, in turn, is a function of temperature and pressure) (Kristensen 1993). The cup anemometer can be considered a first-order filter with a time constant equal to $\ell_\circ/U$, where U is the mean wind speed. It can be interpreted as the length of the column of air which has to pass through the anemometer before it has attained the fraction $1 - \mathrm{e}^{-1} \approx 0.63$ of its it final response to a small change in wind speed.

It is an interesting question whether the cup anemometer responds fast enough to be useful in measuring the stream-wise turbulent fluctuations of the small eddies in the atmospheric surface layer. In other words, can it be used for determining the turbulence intensity? First one must realize that the best temporal resolution of the cup anemometer signal corresponds to one full revolution of the cup rotor. This is so because the rotation rate is not constant, even for a constant wind; the rotor “wobbles” in its rotation, as demonstrated quite clearly by Coppin (1982). The limit, $2\pi\ell$, in spatial resolution means that eddies of smaller linear dimensions can under no circumstances be resolved and their contribution to the total variance be included in the determination of the “cup-anemometer variance”. For the Risø P2546A model $\ell = 0.2$ m which means that it is meaningless to consider eddies with “diameters” smaller than about 1.2 m as measurable flow quantities when using this instrument. Another limitation in resolution is the magnitude of the distance constant $\ell_\circ$ which, as shown by Kristensen & Hansen (2002), is about 1.8 m for the Risø P2546A model. Eddies smaller than $\ell_\circ$ will be “smoothed out” and contribute with lesser weight in the measured variance (and thereby the turbulence intensity). However, the linear dimensions of dominant eddies in the atmospheric surface layer are about five times the height over the surface and larger. Since measurements are usually carried out at heights of more that 10 m, the cup anemometer may very well qualify as a “turbulence instrument”. The aforementioned asymmetric response to increase and decrease in wind speed does not influence the determination of the variance or even of higher order moments (Kristensen 2000).

Another anemometer of the rotating type is the more fragile propeller. Often it is mounted on a wind vane to align the horizontal propeller axis with the wind direction. For this instrument, the prop-vane, the response is symmetric to increases and decreases in the wind speed. Further the response to wind speed changes is usually faster than that of a cup anemometer, at least when the propeller axis is parallel to the wind direction. When measuring the mean wind, however, there are some bias sources. One is the angular response, determined by the angle between the wind speed and the wind direction. Usually the response decreases with this angle and, since the vane will always lag behind, there will be a negative bias. Another source relates to the construction of the prop-vane for which it is not always possible to have the center of the propeller on the axis of the wind vane. The propeller will therefore have an eigenmotion with respect to the air and this will cause a positive bias. A discussion of the prop-vane has been given by Kristensen (1994). It seems that the signal bias is more difficult to estimate than is the case for the cup anemometer.

Finally, it seems relevant to compare the cup anemometer to the sonic anemometer. This instrument measures, over a certain path, with any orientation in space, the velocity of sound along and opposite the wind velocity component along that path, which in currently available sonics has a length of about 0.1 to 0.2 m. It is possible to measure simultaneously, ten to twenty times a second, the wind velocity components in three different directions with a very high spatial as well as temporal resolution. Since the technique is based on a ‘first principle’—the velocity of sound—the calibration can theoretically be calculated. However, flow distortion from the tranducers, i.e. wakes from the transmitters and receivers of the sound pulses, and the temperature dependence of the velocity of sound makes the real calibration of the instrument very complicated. It is necessary to take into account temperature as well as the magnitude and orientation of the wind velocity when calibrating the instrument in a wind tunnel. Many of these effects can be reduced by an on-line signal conditioning provided by the manufacturer, but even then one should not expect a better accuracy of the measured mean wind than about 5 percent (Mortensen 1994). The turbulence intensities can be determined with an accuracy of 10 to 15 percent, which is quite acceptable. The sonic anemometer is a good instrument for measuring the fine spatial and temporal structure of all three wind velocity components.

In conclusion, the cup anemometer, which can determine the wind speed with an accuracy of about 1 percent, seems to be an excellent, perhaps even the best, instrument for measuring the streamwise wind speed, both the mean and the turbulence intensity.

References

Busch, N. E. & Kristensen, L. (1976), ‘Cup anemometer overspeeding’, *J. Appl. Meteor.* **15**, 1328–1332.

Coppin, P. A. (1982), ‘Cup anemometer overspeeding’, *Meteorol. Rdsch.* **35**, 1–11.

Kaganov, E. I. & Yaglom, A. M. (1976), ‘Errors in wind speed measurements by rotation anemometers’, *Boundary-Layer Meteorol.* **10**, 1–11.

Kristensen, L. (1993), The cup anemometer and other exciting instruments, Technical Report R-615(EN), Risø National Laboratory.

Kristensen, L. (1994), Cups, props and vanes, Technical Report R-766(EN), Risø National Laboratory.

Kristensen, L. (1998), ‘Cup anemometer behavior in turbulent environments’, *J. Atmos. Ocean. Technol.* **15**, 5–17.

Kristensen, L. (1999), ‘The perennial cup anemometer’, *Wind Energy* **2**, 59–75.

Kristensen, L. (2000), ‘Measuring higher-order moments with a cup anemometer’, *J. Atmos. Ocean. Technol.* **17**, 1139–1148.

Kristensen, L. (2002), ‘Can a cup anemometer ‘underspeed’, a heretical question’, *Boundary-Layer Meteorol.* **103**, 163–172.

Kristensen, L. & Hansen, O. F. (2002), Distance constant of the Risø cup anemometer, Technical Report R-1320(EN), Risø National Laboratory.

Kristensen, L., Hansen, O. F. & Højstrup, J. (2003), ‘Sampling bias on cup anemometer mean winds’, *Wind Energy* **6**, 321–331.

Middleton, W. E. K. (1969), *Invention of Meteorological Instruments*, The Johns Hopkins Press, Baltimore, MD.

Mortensen, N. G. (1994), Wind measurements for wind energy applications—a review, *in* ‘Proceedings of the 16th British Wind Energy Association Conference’, Stirling, Scotland, pp. 353–360.

Papadopoulos, K. H., Stefanatos, N., Paulsen, U. S. & Morfiadakis, E. (2001), ‘Effects of turbulence and flow inclination on the performance of cup anemometers in the field’, *Boundary-Layer Meteorol.* **101**, 77–107.

Patterson, J. (1926), ‘The cup anemometer’, *Trans. Roy. Soc. Canada, Ser. III* **20**, 1–54.

Schrenk, O. (1929), ‘Über die Trägheitsfehler des Schalenkreuz-Anemometers bei schwankender Windstärke’, *Z. Tech. Phys.* **10**, 57–66.

Wyngaard, J. C. (1981), ‘Cup, propeller, vane, and sonic anemometers in turbulence research’, *Ann. Rev. Fluid Mech.* **13**, 399–423.

Wyngaard, J. C., Bauman, J. T. & Lynch, R. A. (1974), Cup anemometer dynamics, *in* ‘Proc. Flow, Its Measurements and Control in Science and Industry’, Vol. 1, Instrument Society of America, Pittsburg, PA, pp. 701–708.