Technical University of Denmark

A Procedure for Classification of Cup-Anemometers

Friis Pedersen, Troels; Paulsen, Uwe Schmidt

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A PROCEDURE FOR CLASSIFICATION OF CUP-ANEMOMETERS EWEC 97 DUBLIN

Troels Friis Pedersen, Uwe Schmidt Paulsen
Dpt. of Wind Energy and Atmospheric Physics
Risoe National Laboratory, P.O. Box 49,DK-4000 Roskilde, Denmark

ABSTRACT
The paper proposes a classification procedure for cup-anemometers based on similar principles as for power converters. A range of operational parameters are established within which the response of the cup-anemometer is evaluated. The characteristics of real cup-anemometers are fitted to a realistic 3D cup-anemometer model. Afterwards, the model is used to calculate the response under the range of operational conditions which are set up for the classification. Responses are compared to the normal linear calibration relationship, derived from wind tunnel calibrations. Results of the 3D cup-anemometer model are presented and the influence of overspeeding, angular response and friction in bearings are derived. The results are put into a classification scheme.

1. INTRODUCTION

A variety of cup-anemometers are available on the market. Sizes, cup shapes, body shapes and dimensions vary significantly on different designs. Several investigations have been made to find the best cup-anemometers for wind energy applications and often the cheapest anemometers have come out in front. The question is, though, whether the selection criteria for the specific applications have been based on an adequately detailed investigation of the accuracy of each specific cup-anemometer design. Despite all efforts to improve the accuracy of wind speed measurements it is still difficult to set up relevant objective criteria to classify and select cup-anemometers for given purposes.

The systematic errors and statistical uncertainty components are substantial elements to determine a high quality cup-anemometer. The systematic errors for specific ranges of environmental operational conditions are the ones this paper is concentrating about.

2. THE CLASSIFICATION MODEL

A standardisation of the classification, as for example, of electric power converters, Ref. 1, would make selection of cup-anemometers for wind speed measurements very easy. The classification of electric power converters is based on requirements of accuracy of the instruments being lower than a certain level (classification level) for well-defined operational ranges. When stating the class of an electric power converter you will only have to check that the operational ranges in which you will operate the instrument are within the ranges stated in the classification.

Similar classification principles can be set up for cup-anemometers. The elements of a proposed classification procedure for cup-anemometers are shown in Figure 1. A non-ideal (including friction and angular characteristics) cup-anemometer model and fitting procedures of calibrated data under idealised conditions of the real cup-anemometers are basic elements of this procedure. Adding the ranges of environmental operational conditions and the classification criteria to the elements, one arrives in the bottom of the figure to the classification of the cup-anemometer.

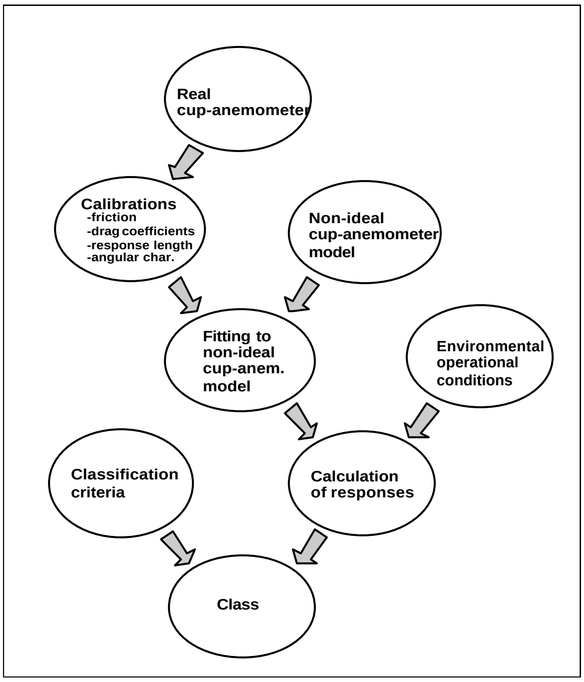

Figure 1. Elements of the classification of cup-anemometers

3. THE CUP-ANEMOMETER MODEL

The model of the cup-anemometer is a physical consistent model, which was shortly described in Ref. 2. It is described here in more detail.

3.1 Aerodynamic forces

The model of the ideal cup-anemometer is simplified to consider only a constant overall aerodynamic drag coefficient on one cup on each side of the cup-anemometer with the cups positioned always with the cup-arms perpendicular to the wind speed. The simplification does not consider the detailed aerodynamics of the rotor, but it is justified when the aerodynamic forces are integrated over one third revolution of a rotor with three cups. The aerodynamic torque on the rotor is:

$$M_A = R\frac{1}{2}\rho A\left((U - R\omega)^2 C_{DH} - (U + R\omega)^2 C_{DL}\right) \qquad (1)$$

where
- R is the rotor arm
- ρ is the air density
- A is the cup area
- U is the wind speed
- ω is the angular speed of the anemometer
- C_{DH} is the high drag coefficient (concave side)
- C_{DL} is the low drag coefficient (convex side)

3.2 Friction

The friction in bearings is the second important force on the cup-anemometer shaft. It is found that the frictional torque is best described by a second order polynomial to the angular speed:

$$M_B = B_0 + B_1 \cdot \omega + B_2 \cdot \omega^2 \qquad (2)$$

The static friction coefficient B_0 has the dimension [kg m^2/s^2], the dynamic friction coefficient B_1 has the dimension [kg m^2/s], and the parabolic friction coefficient B_2 has the dimension [kg m]. The friction may be quite dependent on the temperature, so the friction shall be derived for all temperatures.

3.3 Angular characteristics

When the wind hits the anemometer in an angle not perpendicular to the shaft, the aerodynamic forces changes. The angular characteristics, describing non-perpendicular flow angles, is described as follows. The instantaneous wind vector at the cup-anemometer is:

$$\vec{U} = (u, v, w) \qquad (3)$$

where
- u is the longitudinal wind speed component
- v is the transversal wind speed component
- w is the vertical wind speed component

The instantaneous horizontal wind speed is:

$$\left\langle \vec{U}_{hor} \right\rangle = \sqrt{u^2 + v^2} \qquad (4)$$

The instantaneous length of the wind vector is:

$$\left\langle \vec{U} \right\rangle = \sqrt{u^2 + v^2 + w^2} \qquad (5)$$

The cup-anemometer responds to the actual flow on the rotor. To take this into account in the model it is assumed that the response at different flow angles is determined relative to the response at a right angle of attack. The angle incident on the cup rotor is:

$$\alpha = \mathrm{Atan}\frac{w}{\sqrt{u^2 + v^2}} \qquad (6)$$

The angular characteristics of the cup-anemometer can then be expressed with the function F_α.

$$U = F_\alpha(\alpha)\left\langle \vec{U} \right\rangle \qquad (7)$$

where U is the right angle of attack wind speed that gives the same forces on the rotor as the wind vector inclined to the angle of attack α. F_α can be found in wind tunnel measurements.

3.4 General torque equation with friction

The describing equation of the cup-anemometer is:

$$\begin{aligned} M &= M_A - M_B \\ &= R\frac{1}{2}\rho A\left((U - R\omega)^2 C_{DH} - (U + R\omega)^2 C_{DL}\right) \qquad (8) \\ &\quad - (B_0 + B_1\omega + B_2\omega^2) \end{aligned}$$

The equation is valid for speed ratios ($R\omega/U$) higher than zero and lower than one. The torque equation can be rearranged to:

$$\begin{aligned} \frac{d\omega}{dt} &= \frac{\omega^2}{I}\left(\frac{\rho A R^3}{2}(C_{DH} - C_{DL}) - B_2\right) \\ &\quad - \frac{\omega}{I}\left(U\rho A R^2 (C_{DH} + C_{DL}) - B_1\right) \qquad (9) \\ &\quad + \frac{1}{I}\left(\frac{U^2 \rho A R}{2}(C_{DH} - C_{DL}) - B_0\right) \end{aligned}$$

The solution to the torque equation is found using the Burlish - Stoehr numeric solver to the ordinary differential equation, Ref. 3.

The static solution is not following a straight line, as for usual calibrations, but is almost a straight line:

$$U = \frac{\rho A R^2 \omega (C_{DH} + C_{DL}) + \sqrt{S_q}}{\rho A R (C_{DH} - C_{DL})} \qquad (10)$$

where:

$$\begin{aligned} S_q &= (\rho A R^2 \omega (C_{DH} + C_{DL}))^2 \\ &\quad - 2\rho A R (C_{DH} - C_{DL})\left(\frac{1}{2}\rho A R^2 \omega^2 (C_{DH} - C_{DL})\right) \qquad (11) \\ &\quad - B_0 - B_1\omega - B_2\omega^2 \end{aligned}$$

The usual linear calibration line is found from a normal wind tunnel calibration. The factors C_{DH} and C_{DL} shall be found from the same wind tunnel data when the friction terms are known. The inertia of the rotor might be found from a step response measurement in a wind tunnel.

4. ENVIRONMENTAL OPERATIONAL CONDITIONS

The environmental operational ranges of wind speeds, turbulence, etc. vary quite a lot for different sites. For a classification of cup-anemometers it is appropriate to select a range which covers a substantial range of wind energy applications. For this purpose we get good help from international standards. The IEC design code, Ref. 4, specifies relevant environmental operational ranges for wind turbines. These ranges are supposed to cover the most applications, but special conditions may be applied when found necessary.

4.1 Mean wind speeds

Most wind speed measurements in wind energy applications are related to wind resource and wind utilisation purposes and for these purposes 10 minute averages are used. Below 4 m/s the power in the wind is insignificant and above 16 m/s, the power from the wind turbine is regulated to be almost constant and independent of the wind speed. At 25 m/s the wind turbines are normally stopped. For wind energy related applications the wind speed range of 4-16 m/s is therefore selected for cup-anemometer classification purposes. A 10 min. time series of data with a mean wind speed of 8 m/s (u-component) and 20% turbulence intensity, was generated with a sample frequency of 32 Hz, using the Mann model, Ref. 5. This time series was used for all calculations. The time series was recalculated to other mean wind speeds and turbulence intensities in a straight forward way.

4.2 Turbulence intensities

The IEC design code, Ref. 4, gives good guidance as to the relevant range of turbulence intensities. A formula specifies the maximum standard deviation of the wind speed for a given fractile of probability. For a 95% fractile and for high turbulence (Ref. 4, case A) we have I_{15}=0,18 and a=2, and we get:

$$s_1 = 1{,}13m/s + 0{,}12V_{hub} \Rightarrow Ti = \frac{1{,}13m/s}{V_{hub}} + 0{,}12 \qquad (12)$$

Completely constant wind speeds are never seen. The lowest turbulence intensities that are considered to be relevant are 5% at all wind speeds. Figure 2 shows the ranges of turbulence intensities.

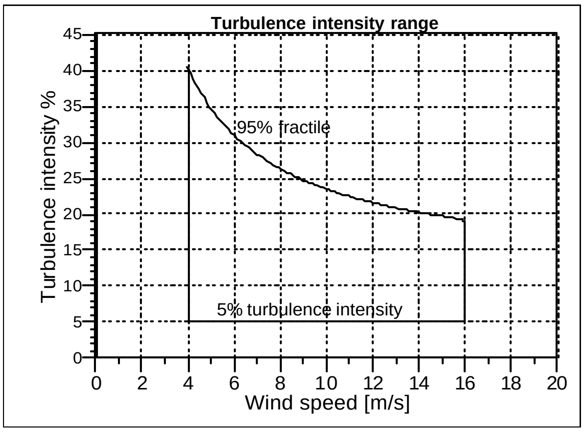

Fig. 2 Turbulence intensity as function of wind speed

4.3 Air temperature

The environmental air temperature is the temperature that the cup-anemometer is exposed to, but not necessarily the temperature of the bearings, which might be heated in several types of cup-anemometers. The air temperature ranges of operational wind turbines are according to the IEC design code, Ref. 4, -10° to 40° for normal conditions and -20° to 50° for extreme conditions. For this analysis the normal conditions have been selected.

4.4 Air density

The air density is affecting the ratio of frictional forces to the aerodynamic forces. Wind turbine altitudes are considered to range between sea level and 2000m, and for these altitudes we get a range of 1,225 to 1,006 kg/m^3, according to ISO Standard Atmosphere, Ref. 6. For a constant altitude an air density range of about $\pm$10% is assumed. On this basis a total air density range of 0,900 to 1,350 kg/m^3 is used. The air humidity variations are assumed included in the air density range, and not to affect cup-anemometers in other ways than through the air density.

4.5 Slope of terrain

The slope of the terrain may change the wind vector components. Wind turbine sites and power performance measurements are performed also in mountainous terrain where the slope of the terrain might be high. The inflow to the cup-anemometer might thus be constantly skew. Wind turbines are known to be placed at quite high slopes or on top of cliffs, where the vertical wind component might be very high. To cover the most applications, but not extreme cases, a range of slopes of -10° to 10° is used for this classification analysis.

4.6 Summary of environmental operational conditions

A summary of the environmental operational ranges for the classification are shown in the table below.

Table 1 Summary of environmental operational ranges

Parameter	Range	
	Minimum	Maximum
Wind speed (10min)	4m/s	16m/s
Turbulence intensity	5%	(1,13m/s/V_{hub}+ 0,12) 100%
Air temperature	-10°C	40°C
Air density	0,90 kg/m^3	1,35 kg/m^3
Slope of terrain	-10°	10°

5. CUP-ANEMOMETER DATA

The data that shall be derived for a cup-anemometer for a classification are those that describes the full cup-anemometer model: rotor arm R, cup area A, rotor inertia I, high and low drag coefficients C_{DH} and C_{DL}, friction coefficients B_0, B_1, B_2 for temperatures from -10°C to 40°C, the angular characteristics F_α, and the normal linear calibration line with the gain a and offset b.

6. EXAMPLE CUP-ANEMOMETER

The example cup-anemometer data for the analysis are derived for a RISØ cup-anemometer. The data are realistic, but not accurate on all parameters. Angular characteristics are shown in Fig. 3. Ideal sampling of the angular speed is assumed. The calibration line is taken from a linear regression of data from the model in the range 4-16m/s at 15°C (simulated wind tunnel calibration): U=a*ω+b, where a=0.19654 m/rad and b=0.20042m/s and r^2=0.999985.

Table 2 RISØ cup-anemometer data

Cup diameter:		0.070 m	
Rotor arm R:		0.058 m	
Rotor inertia I:		0.00006 kg m^2	
High cup drag coefficient C_{DH}:		1.2	
Low cup drag coefficient C_{DL}:		0.36	
Friction coefficients	B_0 kg m^2/s^2	B_1 kg m^2/s	B_2 kg m^2
-10 °C	0.000154	0.00000070	0.0000
15 °C	0.000077	0.00000035	0.0000
40 °C	0.000069	0.00000032	0.0000

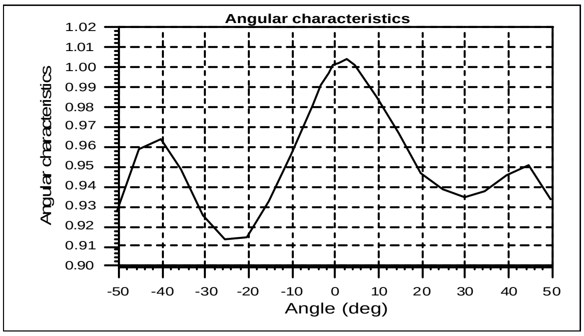

Fig.3 Angular characteristics of RISØ cup-anemometer, from Ref. 5

7. CALCULATION OF RESPONSES

For all the environmental operational ranges (minimum and maximum values, except for ranges that are not giving homogenous increasing or decreasing deviations), the responses of the cup-anemometer are calculated with the model, giving the angular speed of the cup-anemometer. The angular speed of the cup-anemometer is then converted to the "measured" wind speed, using the linear calibration curve, and averaged over 10 minutes. The averaged 10 minute values of the length of the wind vector and the horizontal wind speed are also calculated. For the example cup-anemometer, the deviations of the averaged wind vector from the "measured" values are shown in Fig. 4, when used as a wind vector instrument. The corresponding values for a horizontal wind speed instrument are shown in Fig. 5. The relative deviations are shown in Fig. 6 and 7.

8. CLASSIFICATION

The classification of the instrument, from the data in Fig. to 7, should follow straight forward classification criteria. The relative deviations in Fig. 6 and 7 are substantially higher at the low wind speeds than at the higher wind speeds. A relative classification envelope of the data is thus not appropriate. The absolute deviations are much more constant for different wind speeds. An absolute classification envelope is thus a good criteria for the classification. This means that the highest absolute deviation determines the classification of the cup-anemometer. The classification for the example cup-anemometer is thus a class 0.9m/s wind vector instrument and a class 0.6m/s horizontal wind speed instrument. This means, that the example cup-anemometer is a substantial better instrument for measuring horizontal wind speeds than wind vectors, which it is also well-known for.

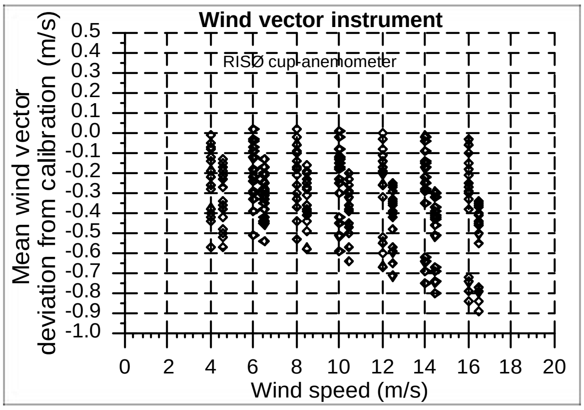

Fig. 4 Deviations from linear calibration line

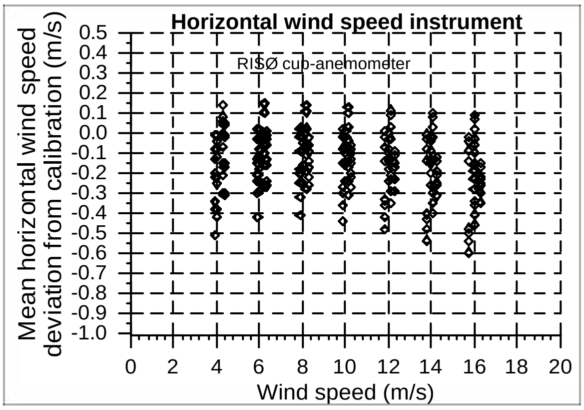

Fig. 5 Deviations from linear calibration line

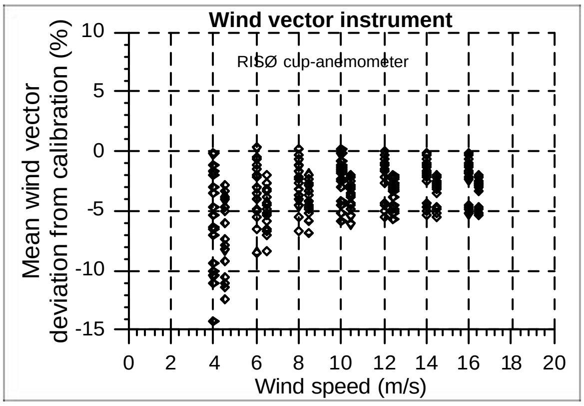

Fig. 6 Relative deviations from linear calibration line

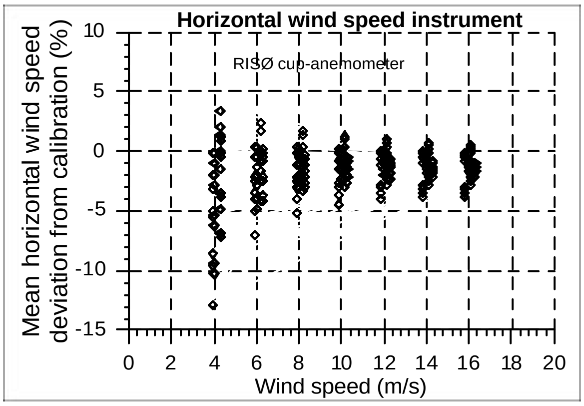

Fig. 7 Relative deviations from linear calibration line

9. DISCUSSION

The calculated deviations are quite high. The example cup-anemometer is normally considered as a precise instrument, but it is influenced very much by the friction and angular characteristics, which are normally not taken into account in wind speed measurements. Fig. 8 to 11 shows the deviations for the example cup-anemometer as a horizontal wind speed instrument for 8m/s wind speed when varying the slope, turbulence intensity, air temperature and air density.

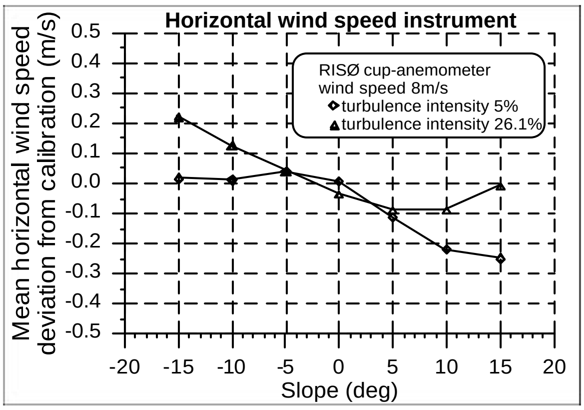

Fig. 8   Deviations due to slope of terrain for air temperature 15°C and density 1.225kg/m^3

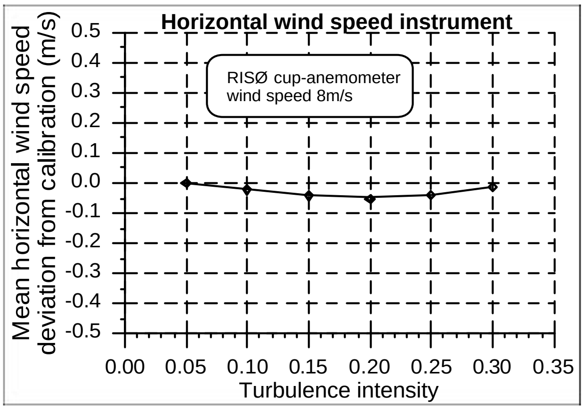

Fig. 9   Deviations due to turbulence intensity for flat terrain and air temperature 15°C and density 1.225kg/m^3

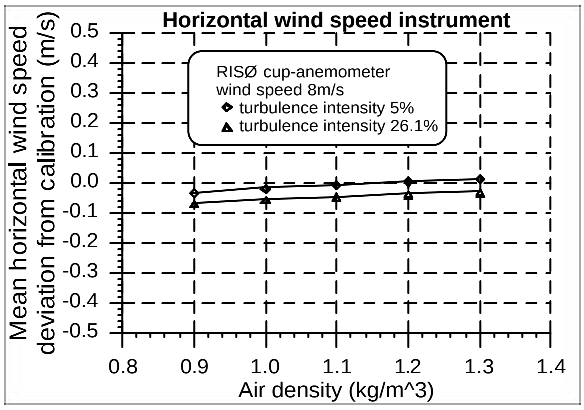

Fig. 10   Deviations due to air density for flat terrain and air temperature 15°C

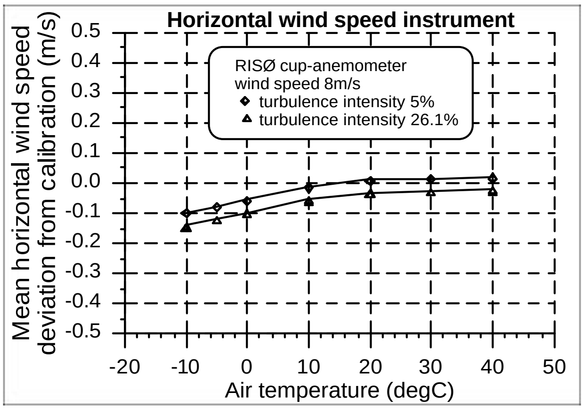

Fig. 11   Deviations due to air temperature for flat terrain and air density 1.225kg/m^3

The deviations with varying slope demonstrates very high influence due to the angular characteristics. It is seen to be the most dominant effect. The air temperature is seen to be the second dominant effect, while the influence due to the air density and turbulence for this example cup-anemometer are very small. In Fig. 12, calculations are shown for the example cup-anemometer without friction and with a flat angular characteristics being used as a wind vector instrument. It is seen that for this case, where only the dynamics of the example cup-anemometer are present, it deviates very little. This indicates, that the distance constant of the cup-anemometer is relatively unimportant to the classification.

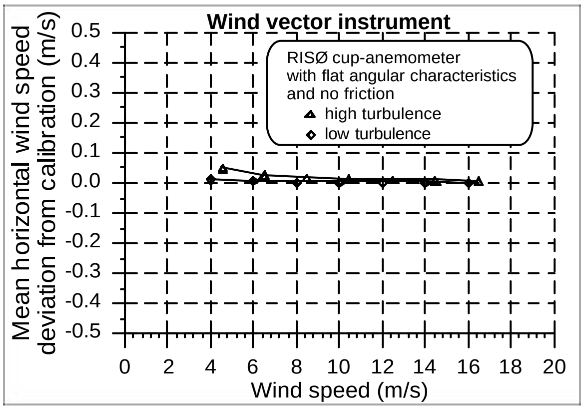

Fig. 12 Deviations due to dynamics ("overspeeding")

The example cup-anemometer is not a "worst case" example. It is a well-known fact, Ref. 8, that angular characteristic are very different and very far from optimum for different cup-anemometers on the market. Comparison of measurements of different types of cup-anemometers when put close together in the free atmosphere also show significant differences. Deviations of 10% have been mentioned. Cup-anemometers on the market are therefore expected to have similar classes as the example cup-anemometer, whether they are better wind vector or horizontal wind speed instruments.

10. CONCLUSIONS

A procedure for classification of cup-anemometers was presented, and an example cup-anemometer was put into the classification scheme. The classification analysis showed that:

- a procedure is now present for classification of cup-anemometers, this being based on a physical consistent cup-anemometer model, which calculates maximum deviations from calibration lines for wind vector or horizontal wind speed instruments for specified ranges of operational conditions
- significant deviations were found for a regular example cup-anemometer, these being due to angular characteristics, friction and dynamics, in that order
- the wind energy community will need to specify the type of cup-anemometers to be used for different applications: wind vector or horizontal wind speed instruments
- with the significant deviations found, there is a need to classify several existing cup-anemometers
- the proposed classification procedure is an excellent tool for selection of the most appropriate cup-anemometers for different applications and for development of a new generation of cup-anemometers

11. ACKNOWLEDGEMENT

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