Quantification of Linear Torque Characteristics of Cup Anemometers with Step Responses

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Quantification of Linear Torque Characteristics of Cup Anemometers with Step Responses

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abstract

This report outlines a method for determination of torque characteristics of cup anemometers based on a partial linear model of torque coefficient relationship. The work was undertaken as part of the UPWIND project part 1A2.1 on metrology, and was identified as needed for revision of the IEC61400-12-1 standard on power performance measurements. The step response model of the IEA-11 document intrinsically leads to linear torque coefficient curves for step responses from low or high speed ratios. The slopes of the linear torque coefficient curves can thus be determined from the step response time constants. The standard ISO 17713-1 recommends step response data in the speed ratio range 30-75% to be used. This seems to be in a range that is outside of the usual range being used in classification according to IEC61400-12-1. In practice, a range closer to equilibrium speed ratios should be used; 50-98% for speed-up step responses and 150-102% for speed-down step responses. A stepwise procedure is proposed, where the step response method may be improved by adding more inertia to the rotor to extend the data and to reduce torque ripples due to the cups.

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Preface

This report outlines a method for determination of torque characteristics of cup anemometers based on a partial linear model of torque coefficient relationship. The work was undertaken as part of the UPWIND project part 1A2.1 on metrology, and was identified as needed for revision of the IEC61400-12-1 standard on power performance measurements. The annex I and J of the standard needed an easier method for determination of torque characteristics of cup anemometers, and measurement of torque characteristics through step responses was identified as a potential solution to the problem.

1 Introduction

The standard IEC61400-12-1 on power performance measurement [1] requires cup anemometers to be classified according to the normative Annex I. An informative Annex J proposes methods for determination of physical characteristics such as aerodynamic torque characteristics. The described method uses wind tunnel measurements where a thin rod is attached to the cup anemometer rotor and extended to the outside of the flow. Here a torque sensor and a motor is connected with the rod. The torque is then measured for typical wind speeds and rotational speeds of the cup anemometer. The torque measurements are normalized to obtain a generalized torque coefficient curve that is normally not linear. Meanwhile, if the torque coefficient above and below equilibrium speed ratio (tunnel calibration condition) both can be approximated to linear curves going through the equilibrium speed ratio point, then it might be possible to determine the linear curves with two step responses, one starting from below and one from above tunnel wind speed. If such a method could be feasible this might be an easier method for classification of cup anemometers. This report describes an investigation of the consequences of making classification of cup anemometers with such partial linearised torque coefficient curves.

2 Basic torque characteristics of cup anemometers

The generalised torque coefficient curve of a cup anemometer [1, annex J] is defined as the torque coefficient versus the speed ratio. The torque coefficient is related to the aerodynamic rotor torque as:

$$C_{QA} = Q_A / (\frac{1}{2}\rho A R u^2)$$

The speed ratio λ is defined as:

$$\lambda = \frac{\omega R}{U - U_t}$$

In case the torque coefficient curve can be assumed linear on either side of the equilibrium speed ratio the torque coefficient can be expressed as:

$$\begin{cases} \lambda \leq \lambda_0 \colon C_{QA} = \kappa_{low}(\lambda - \lambda_0) \\ \lambda > \lambda_0 \colon C_{QA} = \kappa_{high}(\lambda - \lambda_0) \end{cases}$$

Where $\lambda_0 = R/A_{cal}$ is the equilibrium speed ratio.

When determining the torque relations we consider the friction in bearings being negligible. Thus the calibration coefficients relates to the speed ratio as:

$$U = A_{cal}\omega + B_{cal} = \frac{A_{cal}N}{2\pi} f + B_{cal} = \frac{R}{\lambda_0}\omega + U_t$$

3 Linearized torque characteristics of typical cup anemometers

3.1 Torque characteristics of typical cup anemometers

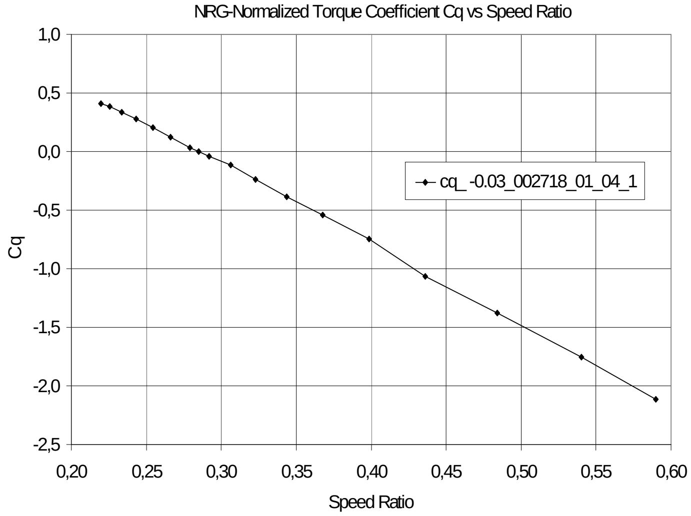
The analysis is based on measurements of torque coefficients made in the FOI wind tunnel by Jan-Åke Dahlberg in the ACCUWIND project [2]. The cup anemometers under consideration are: Risø P2546, Thies First Class, Vector, Vaisala and NRG Maximum 40, see Fig 1. Main data of the cup anemometers are shown in Table 1. The measured torque coefficient curves determined in the ACCUWIND project are shown in figures 2-6.

Table 1 Main data of cup anemometers analysed in ACCUWIND project [2]

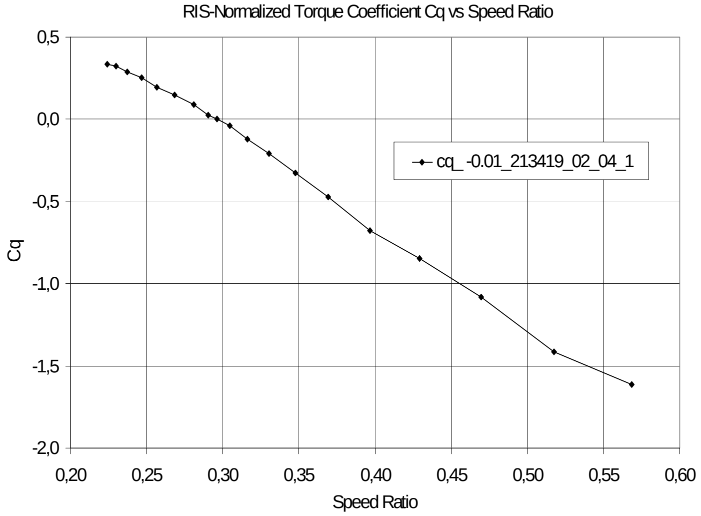
	NRG	RISØ	THIES-FC	VAISALA	VECTOR
Cup diameter (mm)	51	70	80	54	51
Projected cup area A (mm^2)	2000	3850	5030	2290	2040
Rotor diameter (mm)	191	186	240	184	155
Radius to cup centre R (mm)	70	58	80	65	52
Pulses/rev	2	2	37	14	25
Rotor inertia I (kg m^2)	$1.01 \cdot 10^{-4}$	$0.992 \cdot 10^{-4}$	$2.8888 \cdot 10^{-4}$	$0.6141 \cdot 10^{-4}$	$0.441 \cdot 10^{-4}$

				
NRG Maximum 40 (NRG)	Risø P2546 (RIS)	Thies First Class (THF)	Vaisala WAA151 (VAI)	Vector L100K (VEC)

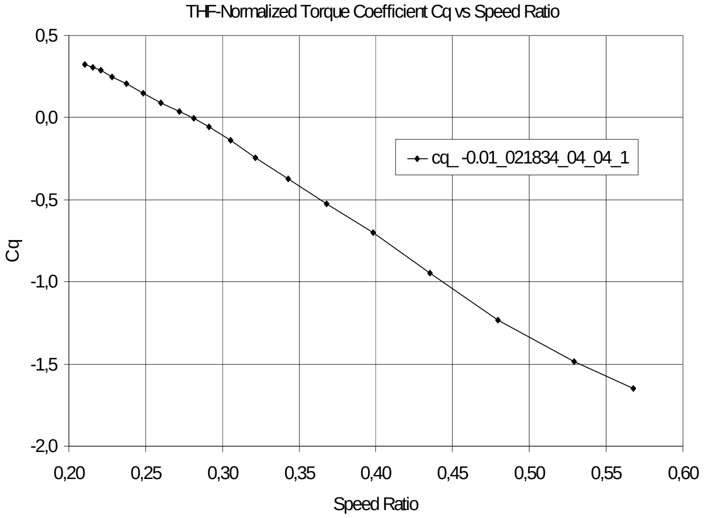
Figure 1 Cup anemometers that was analysed in ACCUWIND project [2]



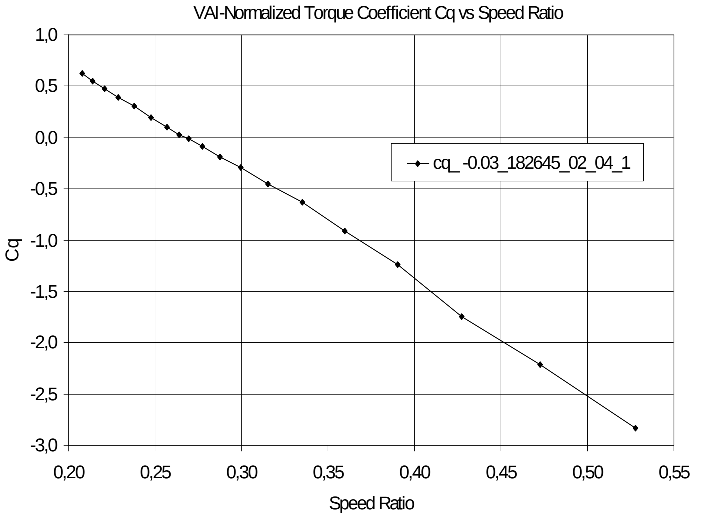
Figur 2 Measured and normalized torque coefficient curve for the NRG anemometer



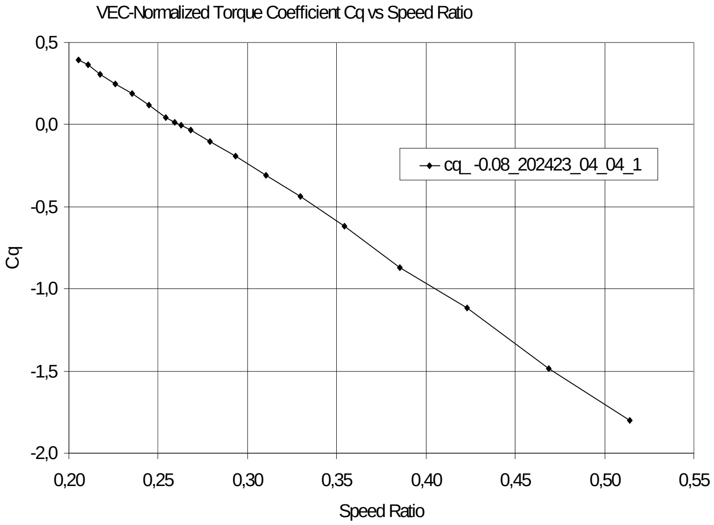
Figur 3 Measured and normalized torque coefficient curve for the RISØ anemometer



Figur 4 Measured and normalized torque coefficient curve for the THIES-FC anemometer



Figur 2 Measured and normalized torque coefficient curve for the VAISALA anemometer



Figur 6 Measured and normalized torque coefficient curve for the VECTOR anemometer

3.2 Linearisation of torque coefficient curves

The torque coefficient curves from figure 2-6 are now linearized on either side of the equilibrium speed ratio. The linear curves were forced through the point of equilibrium speed ratio. The linearized torque coefficient data are shown in table 2 together with derived time constants from inertia in table 1 and with a standard air density of 1.23kg/m^3.

Table 2 Linearised torque coefficient data from linearization of Main data of cup anemometers analysed in ACCUWIND project [2]

	NRG	RISØ	THIES-FC	VAISALA	VECTOR
Equlibrium speed ratio λ_0	0.28461	0.29653	0.28022	0.28964	0.26177
Slope at low speed ratios κ_{low}	-6.5282	-4.9590	-4.6520	-4.8867	-6.6914
Slope at high speed ratios κ_{high}	-6.3595	-6.2140	-5.6901	-4.7652	-6.3128
Ratio $\kappa_{low}/\kappa_{high}$	1.0265	0.7980	0.8176	1.0255	1.0600

4 Classification of cup anemometers with linear torque

The torque coefficient curves from the ACCUWIND project [2] were applied for classification according to the standard IEC61400-12-1 [1]. The results with the full torque coefficient curves and tilt response data measured in the FOI wind tunnel were compared with the results using the linear torque coefficient data from table 2. The results are shown in Table 3.

Table 3 Classification of Risø P2546a using Cm curves or two linearized curves

	Class A	Class A linearized	Class B	Class B linearized
Risø P2546	1.39628	1.39404 (-0.16%)	5.09301	5.0887 (-0.09%)
Thies First Class	1.78074	1.76010 (-1.17%)	3.87461	3.89775 (+0.59%)
Vector	1.82939	1.84430 (+0.81%)	4.48396	4.26761 (-5.07%)
Vaisala	2.22558	2.14491 (-3.63%)	11.9380	11.8207 (-0.98%)
NRG Max40	2.41664	2.52689 (+4.36%)	8.28358	7.98579 (-3.73%)

The comparison of classification results from table 3 shows very good results. The largest deviation is 5.07% on the classification value. Considering that other uncertainties are significant in the whole classification process, this is an indication that linearized torque coefficient curves can be considered sufficient for classification.

5 Existing step response measurement procedures

The linear torque coefficient curves might be determined from step response measurements. There are two standards that consider step response measurements.

5.1 IEA-11 step response measurements

The recommended practice document IEA-11 [3] considers step response measurements in order to determine the time constant and the distant constant. The step response model used in the IEA-11 document is described as:

$$u(t) = u_0 + \Delta u(1 - \exp\left(-\frac{t - t_0}{\tau}\right))$$

Where

$u(t)$ is "measured" wind speed of the cup anemometer

u_0 is the "measured" wind speed at start of the step response at t_0

Δu is the step wind speed

τ is the time constant for the response

In IEA-11 a linear fitting of a conversion of the step response function is proposed:

$$\ln\left(1 - \frac{u(t) - u_0}{\Delta u}\right) = -\frac{t - t_0}{\tau}$$

5.2 ISO 17713-1 step response measurements

The standard ISO 17713-1 [4] on wind tunnel test methods for rotating anemometer performance describes step response measurements in order to determine the distance constant. The model used is described as:

$$U_t = U_f(1 - \exp\left(-\frac{t}{\tau}\right))$$

And the distance constant is determined from:

$$L_U = U\tau$$

The standard requires 10 step response measurements made at 5m/s and 10m/s. The time constant τ is determined from data measured between 30% and 74% of the tunnel wind speed, and the distance constant is determined by multiplying the tunnel wind speed with the time constant.

5.3 Discussion

The two standards claim that the step response measurements are made in order to determine the time constant and the distance constant. ISO 17713-1 also requires that the time constant is derived from the apparent wind speed range 30-74% of tunnel wind speed. This corresponds to speed ratios of 0.3-0.74 of the equilibrium speed ratio. When comparing these speed ratios with the measured torque coefficient curves in figure 2-6 it is obvious that this speed ratio range is far from the equilibrium speed ratio where the most import part of the torque coefficient curves are located. The speed ratios used in figure 2-6 to document the torque coefficient curves are about 75% to 200%.

We know from the ACCUWIND project [2] that the torque coefficient around equilibrium speed ratio is very important for the overspeeding characteristics and the classification determination. It would therefore be beneficial if the step response measurements could express the characteristics of the relevant speed ratios.
In normal field measurements the turbulence is normally Gaussian distributed. This means that wind speeds are distributed about equal on either side of the average wind speed. This also means that the speed ratios are about equal distributed on either side. We should therefore also consider a speed ratio range that corresponds to this distribution.

6 Step response measurements for quantification of linear torque coefficients

When we want to determine torque coefficient characteristics from step response measurements we have to find an appropriate method for determination of the slopes of the torque coefficient curves below and above the equilibrium speed ratio. The following theoretical considerations documents and derive such a procedure.

6.1 Torque equation of a step response

In the following we use the model of the IEA-11 document. We consider a step response from low or high speed ratios. This means from a “measured” wind speed of u_0 to a constant tunnel wind speed of $u_0 + \Delta u$. The general torque equation for a step response can then be expressed by:

$$I \frac{d\omega}{dt} = Q_A = \kappa(\lambda - \lambda_0)\frac{1}{2}\rho A R U^2$$

Her U is the tunnel wind speed $U = u_0 + \Delta u$ and the speed ratio λ is $\lambda = \omega R/(u_0 + \Delta u - U_t)$. This leads to the derivative of the angular speed:

$$\frac{d\omega}{dt} = \frac{1}{2}\rho A R (u_0 + \Delta u)^2 \frac{\kappa}{I}\left(\frac{\omega R}{u_0 + \Delta u - U_t} - \lambda_0\right) = a\omega + b$$

The linear coefficients a and b are:

$$a = \frac{1}{2}\rho A R^2 (u_0 + \Delta u)^2 \frac{\kappa}{I} \frac{1}{(u_0 + \Delta u - U_{t)}}$$

$$b = -\frac{1}{2}\rho A R (u_0 + \Delta u)^2 \frac{\kappa}{I}\lambda_0$$

The derivative of the angular speed is a linear differential equation of first order:

$$\frac{dx}{dt} = p(t)x + q(t)$$

This equation has the general solution:

$$x = \exp\,(P(t) \int \exp\big(-P(t)\big)\, q(t) dt + c * exp(P(t))$$

In this case we have $p(t) = a$ and $q(t) = b$ and a general solution for the angular speed:

$$\omega = c\,\exp(a\,t) - \frac{b}{a}$$

6.2 Determination of linear torque from a step response

The derived expression has exactly the same shape as the step response formula from IEA-11. This is a proof that the step response model from IEA-11 is based on a linear torque coefficient curve. When we equate the expression with the step response equation from IEA-11 we get:

$$a = -\frac{1}{\tau} \Rightarrow \tau = -\frac{1}{a} = -\frac{2I(u_0 + \Delta u - U_t)}{\rho A R^2 (u_0 + \Delta u)^2 \kappa}$$

$$b = \frac{\rho A R^2 (u_0 + \Delta u)^2 \kappa}{2 I A_{cal}}$$

$$c = -\frac{\Delta u}{A_{cal}}$$

And we can derive κ as:

$$\kappa = -\frac{2I(u_0 + \Delta u - U_t)}{\rho A R^2 (u_0 + \Delta u)^2 \tau}$$

With a step response from stand still, where the speed ratio is low, the slope of the torque coefficient slope κ_{low} is determined and with a step response from an overspeeding situation, where the speed ratio is high, κ_{high} is determined. The inertia I is the inertia of the whole rotating setup. If a flywheel is added its inertia must be added to the inertia of the cup anemometer rotor.

7 Step response measurements – an example

An example of a step response is analysed in order to find how well it fits with torque characteristics found from linearization of the actual measured torque coefficient curves. An example of a step-up response made by WindGuard is shown in figure 7. The cup anemometer is a Risø P2546 and the tunnel wind speed is 5m/s. Using the IEA-11 fitting procedure we get the logarithmic expression as function of time as shown in figure 8. The IEA-11 procedure focuses on using the linear data, and obviously from figure 8, some data has to be left out. Figure 9 shows the ln-expression when only using the 30-74% of data as recommended in ISO 17713-1. From the figure it is seen that the data is very limited. This makes the derivation of the slope very sensitive to the actual rotor positioning during the step response and the ripples due to varying cup torque as shown in figure 7.

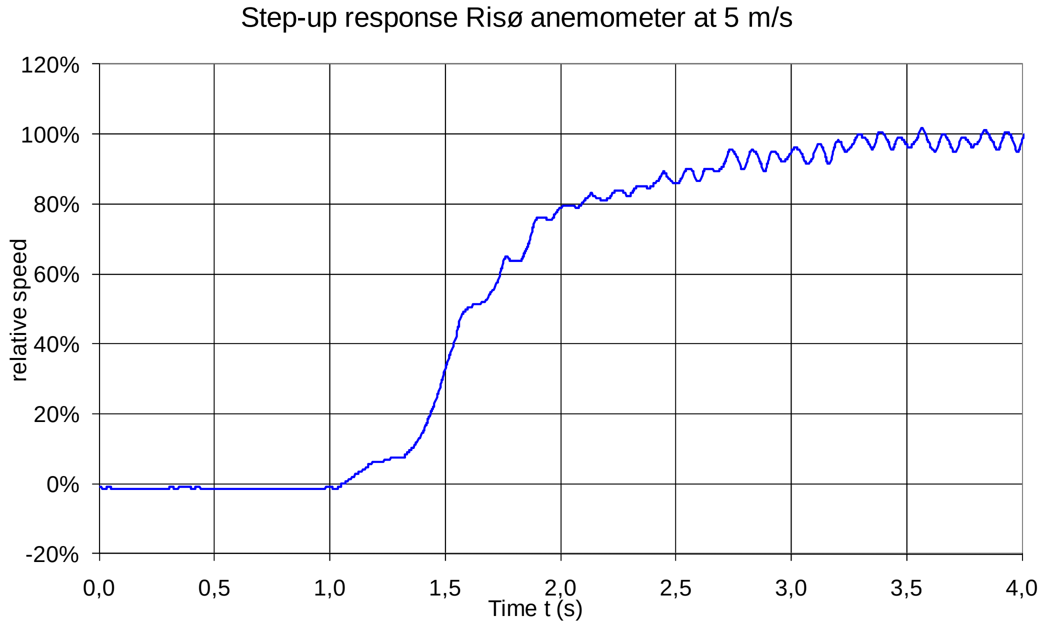


Figure 7 Step-up response of Risø P2546 cup anemometer at 5m/s tunnel wind speed

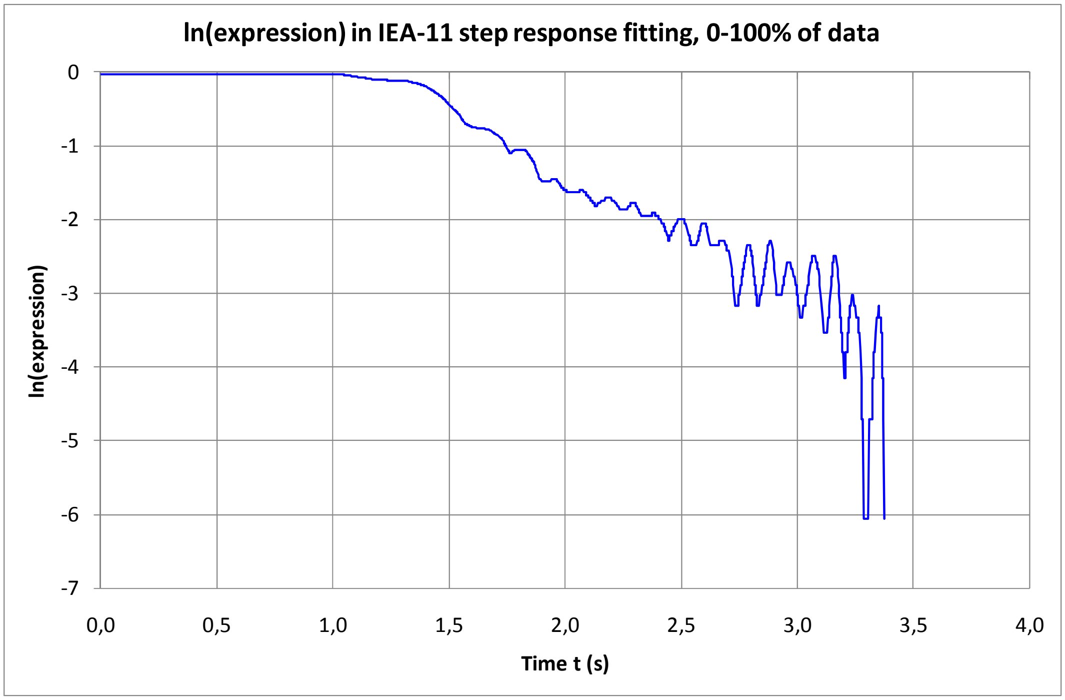


Figure 8 ln-expression from IEA-11 step response fitting procedure using all data

Figure 10 shows the use of a broader data range, which is also more relevant for the expression of the torque close to equilibrium speed ratio. It is seen that the slope is also significantly different (30%) from the shorter range in figure 9. This might be a correct slope for the range of speed ratios because the torque coefficient cannot be considered linear far from equilibrium speed ratio. The curve in figure 10 looks reasonably linear but with ripples that increase when getting close to equilibrium speed ratio. Compared to all data in figure 8 one should not get too close to equilibrium speed ratio. The criteria used here was to stop the range the first time 98% relative speed was reached.

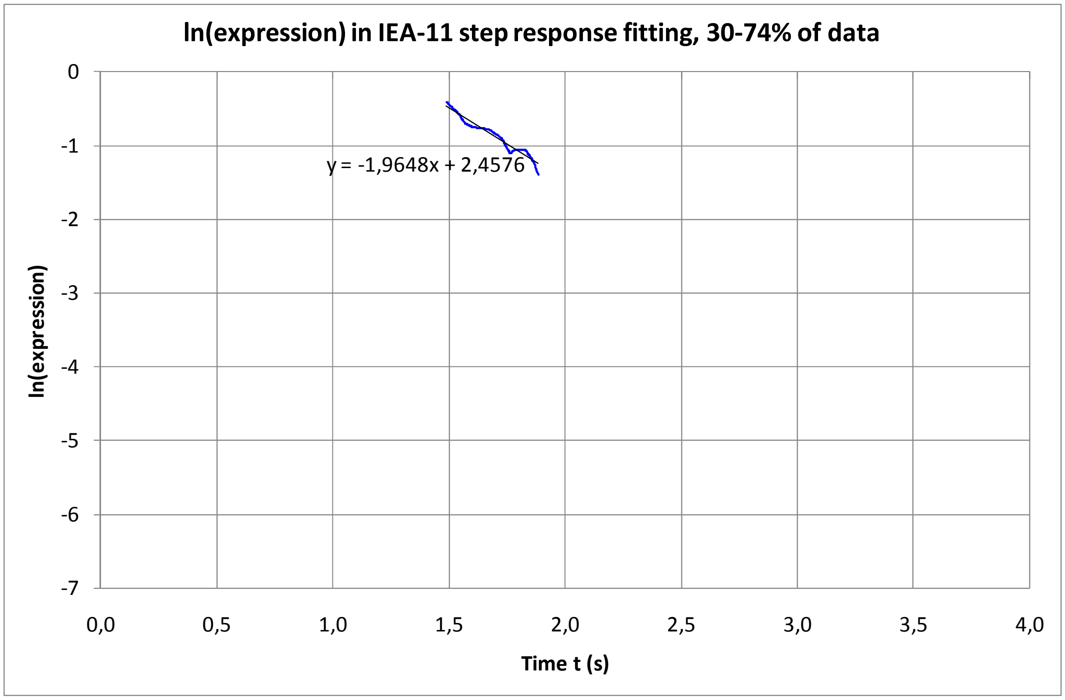


Figure 9 ln-expression from IEA-11 step response fitting procedure using 30-74% of step-up data as recommended in ISO 17713-1

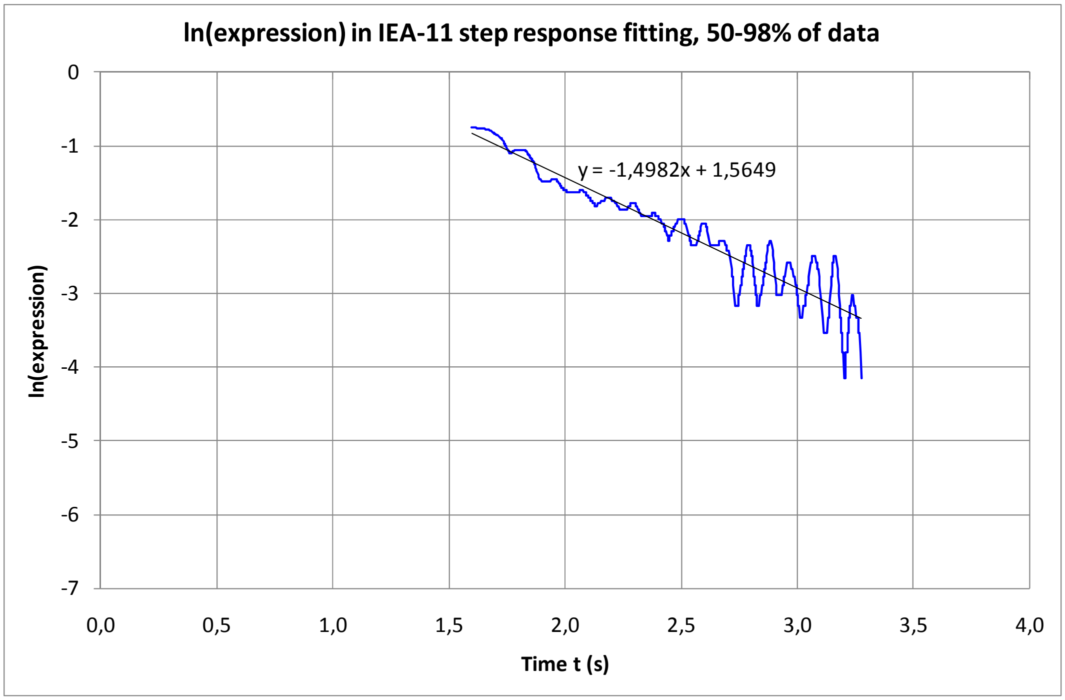


Figure 10 ln-expression from IEA-11 step response fitting procedure using 50-98% of step-up data

Figure 11 shows a speed-down response of the same Risø cup anemometer, first speeded up to 200%. Figure 12 shows the ln-expression for a relative speed range of 150-102%, which seems to cover quite well the essential part of the step response.

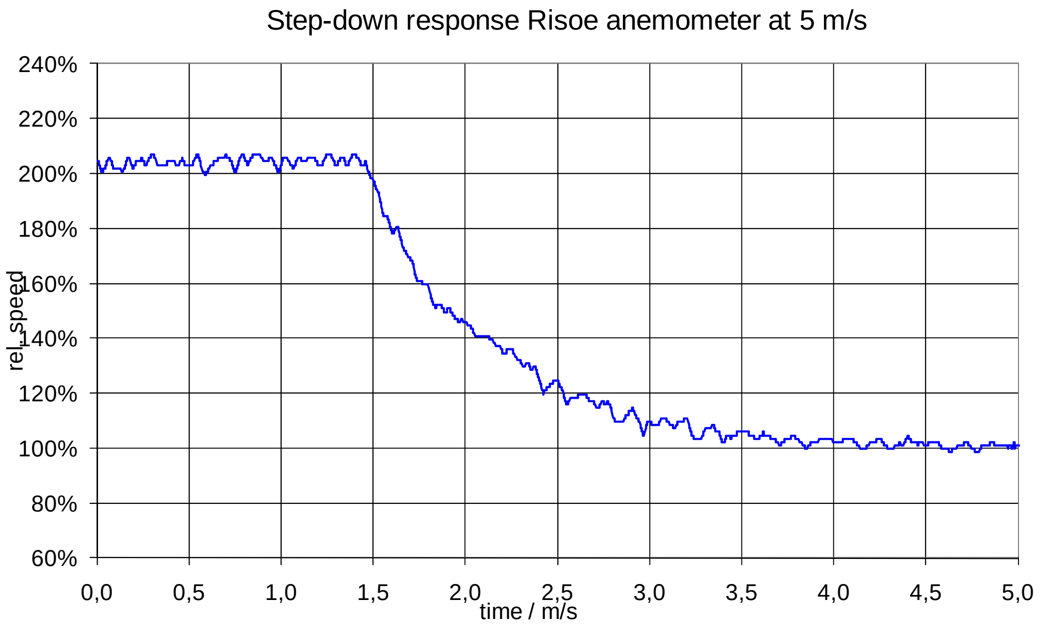


Figure 11 Step-down response of Risø P2546 cup anemometer at 5m/s tunnel wind speed

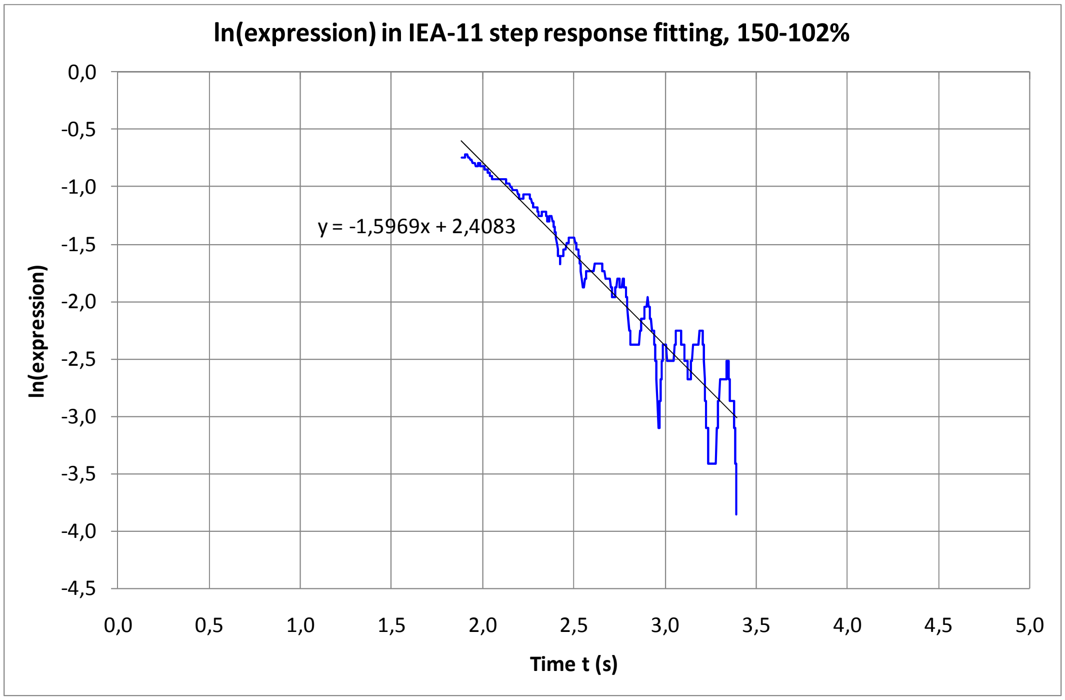


Figure 12 ln-expression from IEA-11 step response fitting procedure using 150-102% of step-down data

The step responses were performed more than once. Table 4 shows slopes of the ln-expression and κ values for three step-up responses and three step-down responses. The average step-up time constant τ_{low} is 0.6970, and the average step-down time constant τ_{high} is 0.5956. The corresponding torque coefficient slope values are κ_{low} equal to -3.493 and κ_{high} equal to -4.088. The results are shown in table 5, where they are compared with the values from linearization of the torque curves from the ACCUWIND project.

Table 4 Step responses of Risø P2546 cup anemometer at 5m/s tunnel wind speed, assuming an air density of 1,23kg/m^3

	Step 1		Step 2		Step 3	
	Ln-exp	τ	Ln-exp	τ	Ln-exp	τ
Step-up	-1.4982	0.667	-1.295	0.772	-1.5335	0.6521
Step-down	-1.750	0.571	-1.696	0.5896	-1.5969	0.6262

Table 5 Slopes of linear torque coefficient curves for Risø P2546 cup anemometer determined with torque measurements according to [2] and with step responses

Risø torque coefficient slopes	Torque measurements ACCUWIND linearised	Torque measurements step responses	Ratio step/ACCUW
Equlibrium speed ratio λ_0	0.29653		
Slope at low speed ratios κ_{low}	-4.9590	-3.493	0.704
Slope at high speed ratios κ_{high}	-6.2140	-4.088	0.658
Ratio $\kappa_{low}/\kappa_{high}$	0.7980	0.8545	1.071

From table 5 it is seen that the step response method gives about 30% lower torque coefficient slopes than the linearized torque from the measurements in the ACCUWIND project. The torque coefficient slope values are proportional to the rotor inertia and the slopes of the ln-expressions, but reverse proportional to the time constants. The reason for the difference might be due to additional 30% inertia in the rotating test equipment during the tests.

8 Maximum dynamic overspeeding

The aerodynamic torque characteristics determines the dynamic overspeeding behaviour when the cup anemometer is exposed to sinusoidal varying wind speed as shown in figure 13 for the Risø P2546 cup anemometer [5].

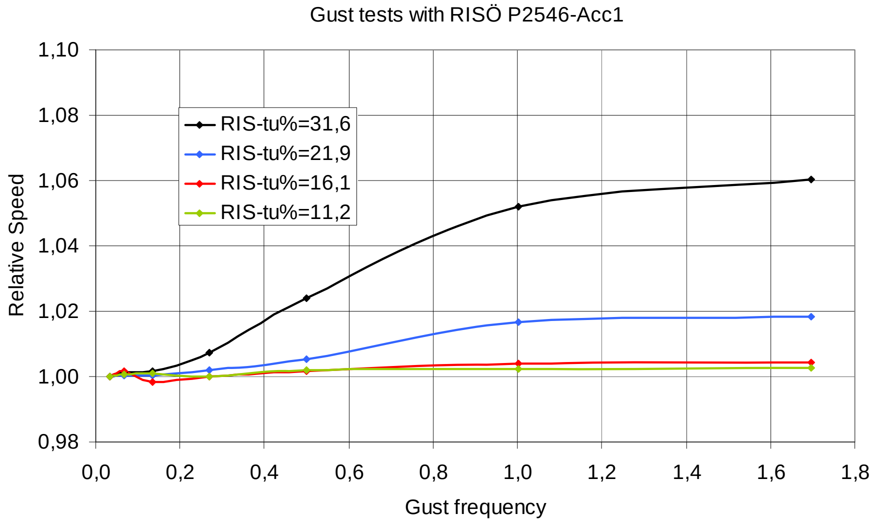


Figure 13 Dynamic overspeeding of Risø P2546 cup anemometer when exposed to sinusoidal varying wind speed, from [5]

Figure 13 shows a typical pattern of overspeeding characteristics. With increasing frequency the overspeeding stabilizes to a constant level, the maximum overspeeding, which is only a function of the turbulence intensity, or in this case the amplitude of the sinusoidal varying tunnel wind speed.
The maximum overspeeding for a partial linear torque coefficient curve can be found by applying a high frequency pulsating rectangular wind speed with an average of u_0 and an amplitude of Δu. In this case we have an average torque over one cycle:

$$Q = \frac{1}{2}\rho AR(u_0+\Delta u)^2\kappa_{high}(\lambda-\lambda_0) + \frac{1}{2}\rho AR(u_0-\Delta u)^2\kappa_{low}(\lambda-\lambda_0)$$

We can then derive:

$$\frac{Q}{\frac{1}{4}\rho AR^2} = \left(\frac{(u_0+\Delta u)^2\kappa_{high}}{u_0+\Delta u-B_c} + \frac{(u_0-\Delta u)^2\kappa_{low}}{u_0-\Delta u-B_c}\right)\omega - \frac{1}{A_c}\left((u_0+\Delta u)^2\kappa_{high} + (u_0-\Delta u)^2\kappa_{low}\right)$$

And for $Q = 0$ we get:

$$\omega = \frac{\frac{1}{A_c}\left((u_0+\Delta u)^2\frac{\kappa_{high}}{\kappa_{low}} + (u_0-\Delta u)^2\right)}{\frac{(u_0+\Delta u)^2}{u_0+\Delta u-B_c}\frac{\kappa_{high}}{\kappa_{low}} + \frac{(u_0-\Delta u)^2}{u_0-\Delta u-B_c}}$$

The overspeeding is derived as:

$$O_s = \frac{\omega-\omega_{\Delta u=0}}{\omega_{\Delta u=0}} = \frac{\left(\left(1+\frac{\Delta u}{u_0}\right)^2 + \left(1-\frac{\Delta u}{u_0}\right)^2\frac{\kappa_{high}}{\kappa_{low}}\right)}{\frac{\left(1+\frac{\Delta u}{u_0}\right)^2\left(1-\frac{B_c}{u_0}\right)}{\left(1+\frac{\Delta u}{u_0}-\frac{B_c}{u_0}\right)} + \frac{\left(1-\frac{\Delta u}{u_0}\right)^2\left(1-\frac{B_c}{u_0}\right)}{\left(1-\frac{\Delta u}{u_0}-\frac{B_c}{u_0}\right)}\frac{\kappa_{high}}{\kappa_{low}}} - 1$$

From this expression we see that the overspeeding is dependent on the ratio between the torque coefficient slopes, the turbulence ($T_i = \Delta u/u_0$) and the term B_c/u_0. For a cup anemometer with a calibration offset of $B_c = 0.20m/s$ and a wind speed of 8m/s the maximum overspeeding is as shown in figure 14. The maximum overspeeding is almost independent of B_c. If set equal to zero the differences would be in the order of 0.0004.

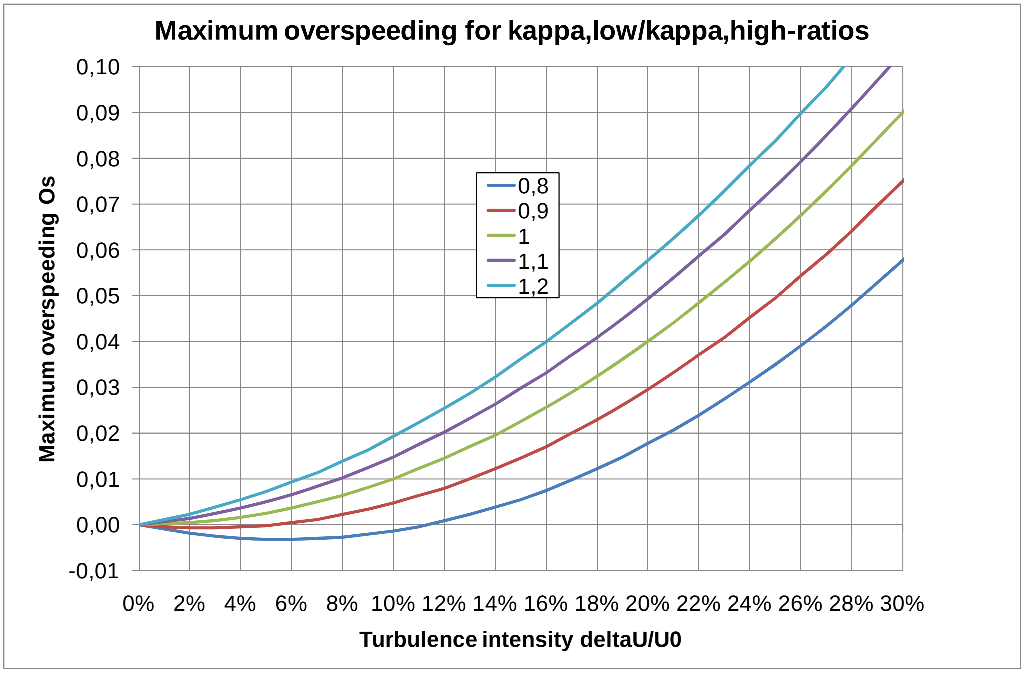


Figure 14 Maximum overspeeding for various turbulence intensities and $\kappa_{low}/\kappa_{high}$- ratios

For a Risø cup anemometer with the κ ratio equal to 0,798 these maximum overspeeding values correspond quite well with the measured maximum overspeeding in figure 13 for various turbulence intensities. This indicates that the dynamic overspeeding in general can be well determined with linear torque coefficients.

9 Proposal for procedural steps for determination of linear torque coefficients with step responses

The measurement of torque characteristics of cup anemometers as required for classification of cup anemometers in the power performance standard IEC61400-12-1 annex J, may be performed by step response measurements in constant speed wind tunnels.

As is seen from the step responses in figures 7 and 11 the step response curves are not smooth. They are superimposed a three per rev variation due to the torque pulse of each cup. The step responses are also very fast so the use of only few pulses per rev increases uncertainty. The step response measurement might therefore be improved by adding inertia to the rotating mass. This will both increase the time of each step response, adding more data to the analysis, and smooth out the step response.

Based on the analysis of the step response method, the following procedural steps are proposed:

1. Make a standard calibration $U = A_{cal} \cdot f + B_{cal}$, where the calibration constants are determined
2. Measure the cup area A as the projection of one cup on a surface parallel to the open side, measure the radius R from the shaft centre of the cup rotor to the centre of the cup, and measure the inertia I of the rotor of the cup anemometer
3. Arrange the tunnel to measure following parameters during step response measurements: time t, tunnel wind speed U_{tunnel}, speed of cup rotor f, temperature T and pressure B; (preferably a high resolution measurement should be used, alternatively three pulses per revolution should be used for a three cup anemometer, and time between pulses should be measured with a resolution of at least 1ms; this could be achieved by optical measurements with a beam going through a cup)
4. Arrange a device to stop the rotor of the cup anemometer without distorting the flow
5. Set tunnel wind speed to 5m/s (re ISO 17713-1) and make 10 step responses from stand still (each step response shall record at least five seconds more after rotational equilibrium has been reached within 2%)
6. Set the tunnel wind speed to 10m/s and make 10 new step responses from stand still
7. Arrange a device that can speed up the cup anemometer rotor to a rotational speed corresponding to 20m/s (this can be achieved with a thin rod attached to the rotor and extended to the outside of the wind tunnel flow; the thin rod might be attached to a flywheel with inertia 4-5 times that of the cup anemometer; a motor that can spin up the rotor and be detached during the step response measurement is connected
8. Set tunnel wind speed to 5m/s and make 10 step responses from up-speeded cup anemometer corresponding to 20m/s
9. Set the tunnel wind speed to 10m/s and make 10 new step responses from up-speeded cup anemometer corresponding to 20m/s
10. Use step response model from IEA-11: $u(t) = u_0 + \Delta \mathrm{u}(1 - \exp\left(-\frac{\mathrm{t}-\mathrm{t}_0}{\tau}\right))$, and use the linearised expression $\ln\left(1 - \frac{u(t)-u_0}{\Delta u}\right) = -(t - t_0)/\tau$ to fit measured data
11. In the measured cup wind speed range 50% to 98% of tunnel wind speed for speed up measurements use the linearised expression and plot the left hand side as the y-axis and time t as the x-axis; then make a linear regression and find the gain factor G; then determine the time constant from $\tau_{low} = -1/G$
12. In the measured cup wind speed range 150% to 102% of tunnel wind speed for speed down measurements use the linearised expression and plot the left hand side as the y-axis and time t as the x-axis; then make a linear regression and find the gain factor G; then determine the time constant from $\tau_{high} = -1/G$
13. Average all time constants from speed up step response measurements to get τ_{low} and average all time constants from speed down step response measurements τ_{high}
14. Determine the equilibrium speed ratio by $\lambda_0 = \frac{2\pi R}{N A_{cal}}$
15. Determine the slope of the torque coefficient curve for low speed ratios: $\kappa_{low} = \frac{2I(u_0+\Delta u-U_t)}{\rho A R^2 (u_0+\Delta u)^2 \tau_{low}}$
16. Determine the slope of the torque coefficient curve for low speed ratios $\kappa_{high} = \frac{2I(u_0+\Delta u-U_t)}{\rho A R^2 (u_0+\Delta u)^2 \tau_{high}}$

10 Conclusions

The step response model of the IEA-11 document intrinsically leads to linear torque coefficient curves for step responses from low or high speed ratios. The slopes of the linear torque coefficient curves can thus be determined from the step response time constants. The intercept of the linear torque coefficient curves, which is the equilibrium speed ratio, is determined from the normal wind tunnel calibration gain value. The standard ISO 17713-1 recommends step response data in the speed ratio range 30-75% to be used. This seems to be in a range that is outside of the usual range being used in classification according to IEC61400-12-1. In practice, a range closer to equilibrium speed ratios should be used; 50-98% for speed-up step responses and 150-102% for speed-down step responses. The step response measurements can fully determine linear torque coefficient characteristics of cup anemometers with the only assumption that the friction in bearings is negligible with respect to determination of aerodynamic torque characteristics. The step response method may be improved by adding more inertia to the rotor to extend the data and to reduce torque ripples due to the cups.

11 References

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