RENEWABLE NRG SYSTEMS

Characterization and Classification of the NRG Class 1 Anemometer for IEC 61400-12-1 Compliance

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5/10/2012

I. Abstract

Under the guidance of Troels Pedersen of DTU Wind Energy Department (formerly RISO National Laboratory), Renewable NRG Systems has characterized and classified the NRG Class 1 Anemometer, a ball bearing version of the NRG #40C Anemometer, according to the guidelines documented in the DTU Wind Energy Department's Accuwind reports and the IEC 61400-12-1 Standard for Power performance measurements of electricity producing wind turbines. Following the Accuwind method and the IEC 61400-12-1 Standard, the Classification Indices of the NRG Class 1 Anemometer are 1.01A and 8.44B, as summarized in Table 1 below.

Table 1 Summary of Classification Indices for NRG Class 1 Anemometers

NRG Class 1 Anemometer S/N	Class A Index	Class B Index
S/N 047	1.07	8.07
S/N 066	0.948	8.80
Average Value	1.01	8.44

This white paper documents the results and supporting work to characterize and classify the NRG Class 1 Anemometer according to the guidelines documented in the DTU Wind Energy Department's Accuwind reports and the IEC 61400-12-1 Standard.

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II. Overview of the Anemometer Classification

Anemometer classification is comprised of three (3) main steps:

1. Quantifying the anemometer error subject to influence parameters including dynamic effects (due to wind turbulence), off-axis (non-horizontal) wind, and bearing friction effects. The method for quantifying anemometer error is based on the Tilt-Response & Torque-Coefficient (TRTC) model described in the DTU Wind Energy Department's Accuwind report (J.-Å. Dahlberg, May 2006). The influence parameters and ranges are summarized in Table 2 below.
2. Classifying the anemometer by assigning an index (k) that bounds the maximum anemometer error. The index is quantified using the following equation:

$$k = 100 \cdot \max \left| \frac{\varepsilon_i}{\frac{U_i}{2} + 5\ \mathrm{m/s}} \right|$$

   where k is the Classification Index, ε_i is the anemometer error in wind speed bin *i*, U_i is the wind speed in bin *i*. The denominator in the above equation is the deviation envelope. So a Classification Index is assigned to an anemometer that bounds its maximum wind speed deviation subject to the stated influence parameters.
3. Classifying at least two (2) anemometers to determine the overall Classification Index of the anemometer per IEC 61400-12-1 (IEC 61400-12-1 Power performance measurements of electricity producing wind turbines). IEC 61400-12-1 Annex I states "At least two examples of a type of anemometer shall be assessed" for the classification of anemometry. Averaging the results of the two (2) classifications is an acceptable method for determining the overall anemometer Classification Indices.

Anemometer dynamics, off-axis response, and bearing friction are measured under laboratory-controlled conditions (see Section entitled Measured NRG Class 1 Anemometer Input Data for details). These measurements are physical inputs into the TRTC anemometer model which quantifies and bounds the error of the anemometer, subject to the influence parameters. The operational range of the influence parameters are summarized in Table 2. "Class A" corresponds to flat terrain sites; "Class B" corresponds to complex terrain sites.

To meet the requirements of IEC 61400-12-1, two (2) NRG Class 1 Anemometers (S/N 047 and S/N 066) were characterized to determine the overall anemometer classification through averaging.

Table 2 Class A and B Operational Ranges

Classification Category	Class A Ideal flat terrain sites		Class B Non-ideal complex terrain sites	
	Min	Max	Min	Max
Wind speed range (m/s)	4	16	4	16
Turbulence Intensity	0.03	0.12 + 0.48/V	0.03	0.12 + 0.96/V
Turbulence Structure $\sigma_u/\sigma_v/\sigma_w$	1/0.8/0.5 Non-isotropic turbulence Kaimal wind spectrum with a longitudinal turbulence scale of 350m		1/1/1 Isotropic turbulence Von Karman wind spectrum with a longitudinal turbulence length scale of 170m	
Air Temperature (°C)	0	40	-10	40
Air Density (kg/m3)	0.9	1.35	0.9	1.35
Average flow inclination (°)	-3	3	-15	15

III. Measured NRG Class 1 Anemometer Input Data

Numerical values of all input data obtained from laboratory tests are included in the NRGBBO-047.cup and NRGBBO-066.cup input files (see attachments). The first five lines of the input file contain anemometer property data (cup radius, area, and moment of inertia) as well as calibration slope and offset. After line five, the input file includes three distinct blocks of measured data: torque, friction, and off-axis response. Data measured on two (2) NRG Class 1 Anemometers (S/N 047 and S/N 066) was used to classify the anemometer. Each of the measured input data is described below.

Wind Tunnel Calibration

The two (2) NRG Class 1 Anemometers were calibrated in Svend Ole Hansen's (SOH) Measnet-certified wind tunnel. Calibrations followed the protocol outlined in IEC 61400-12-1, Annex F. The calibration values for the two (2) anemometers are reported in Table 3 below.

Table 3 Summary of Calibration Values

NRG Class 1 Anemometer	Slope	Offset
S/N 047	0.76572	0.19924
S/N 066	0.76645	0.20439

Angular or Off-Axis Response

Off-axis response of the NRG Class 1 Anemometers was measured in the Svend Ole Hansen (SOH) Measnet-certified wind tunnel. Off-axis response measurements were taken statically, and not with a constant sweep rate, which results in more accurate measurements. Throughout the off-axis response test, a minimum clearance distance of 0.55m is maintained between the anemometer head and any tunnel walls, ensuring reduced uncertainty in the measurements.

Off-axis response of the NRG Class 1 Anemometers was measured at 7, 10, and 13 m/s, subjected to tilt angles ranging from -30 to +30 degrees. A negative tilt angle indicates wind from above; a positive tilt angle indicates wind from below. The off-axis responses for the anemometers (S/N 047 and S/N 066) are plotted in Figure 1 and Figure 2.

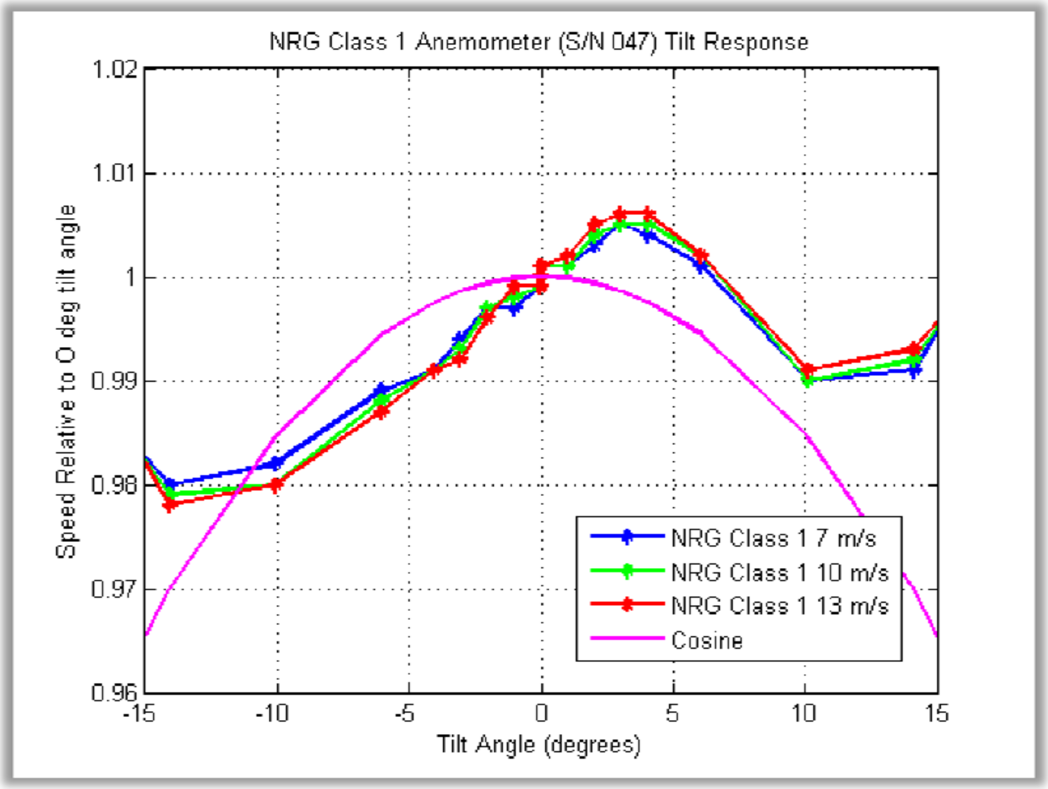

Figure 1 NRG Class 1 Anemometer (SN-047) Tilt Response

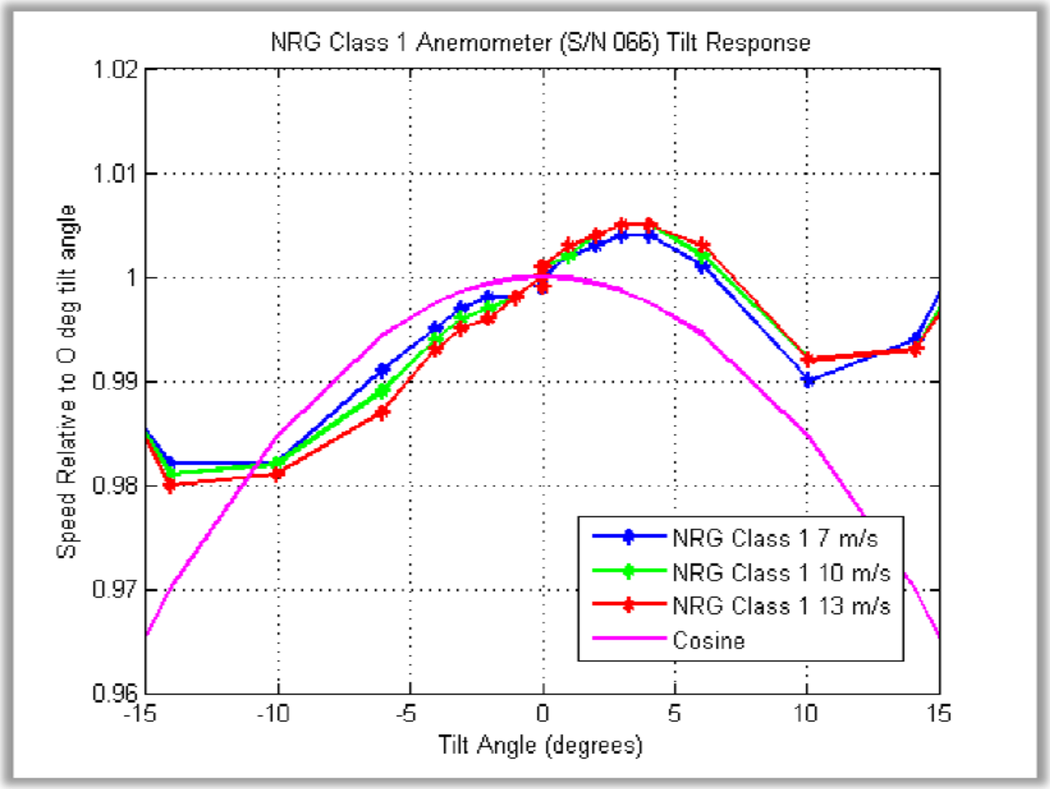

Figure 2 NRG Class 1 Anemometer (SN-066) Tilt Response

Friction

The friction of the NRG Class 1 Anemometers was measured using an NRG-built flywheel decelerator, in accordance with Section 3.6 of the RISO-R-1556 report. The polynomial curve fits of the measured friction data of the NRG Class 1 Anemometers over a temperature range of -30°F to +40°F are plotted in Figure 3 and Figure 4.

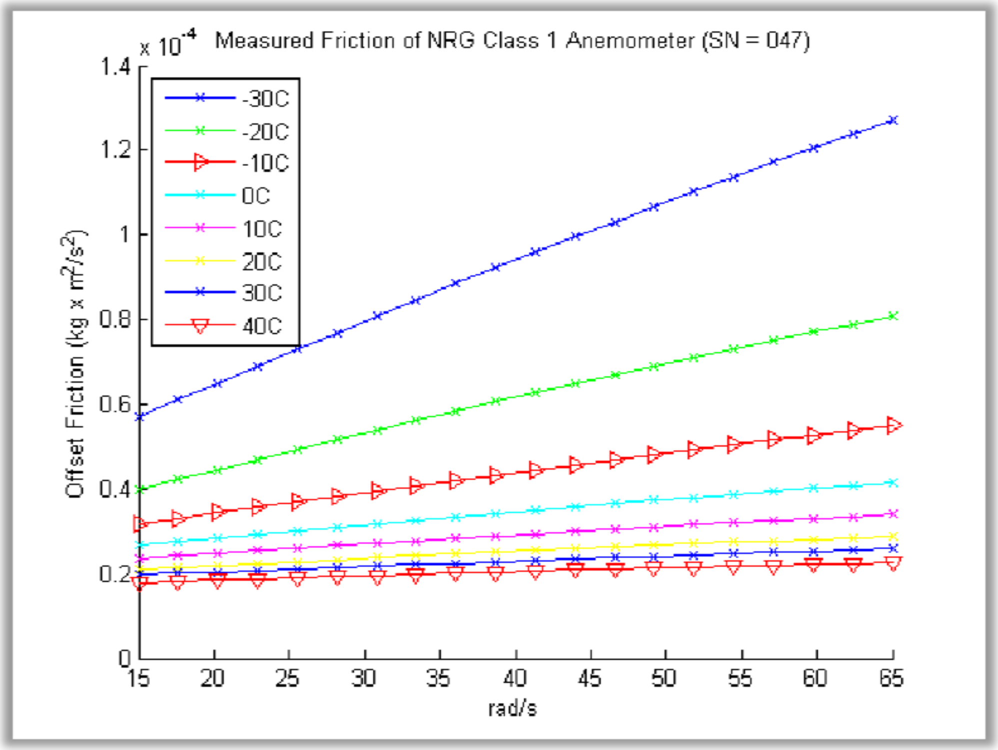

Figure 3 NRG Class 1 Anemometer (S/N 047) Friction Data

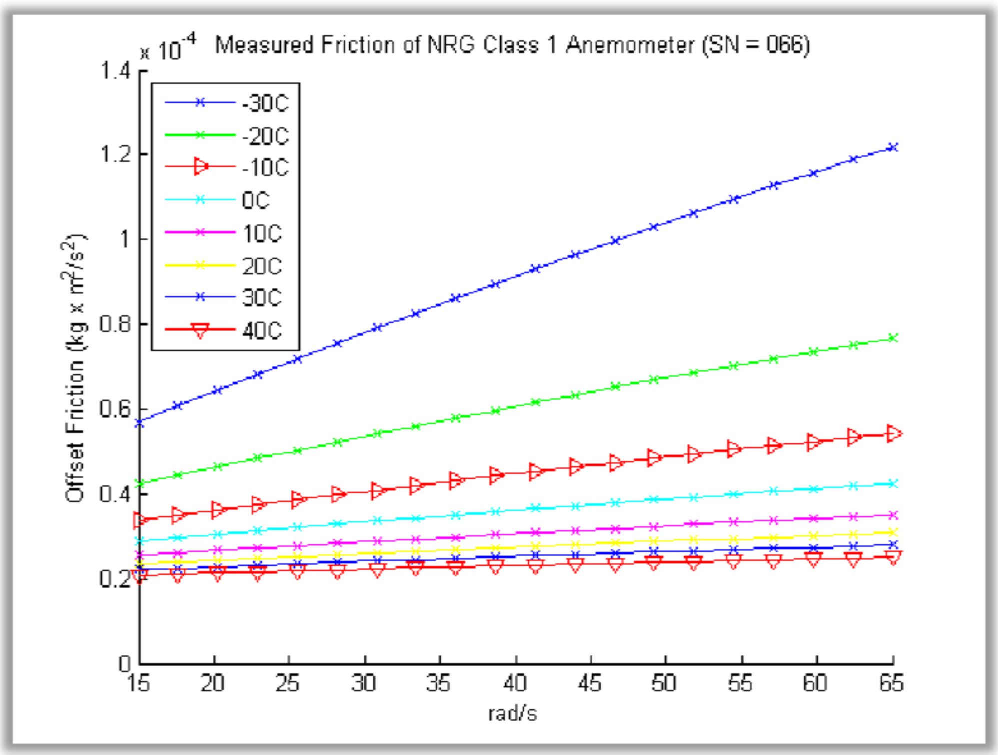

Figure 4 NRG Class 1 Anemometer (S/N 066) Friction Data

Torque

Measured torque data includes frictional torque plus aerodynamic torque, the latter being the dominant source of torque. Torque data measured on the Rulon bearing NRG #40C anemometer was utilized for the NRG Class 1 Anemometer due to constraints in adjusting the torque data set. Specifically, it was not possible to subtract out the frictional torque from the original DTU Wind Energy Department's torque data of the NRG #40C Anemometer and subsequently add-in the frictional torque of the NRG Class 1 Anemometer.

The NRG Class 1 Anemometer employs the identical head as the NRG #40C Anemometer. As such, it is anticipated that the total torque of the NRG Class 1 Anemometer will be close to that of the NRG #40C Anemometer, since the aerodynamic torque dominates the total torque and aerodynamic torque is governed by the anemometer head. The approach of using the NRG #40C torque data for the NRG Class 1 Anemometer is conservative because the NRG Class 1 Anemometer possesses less frictional torque than the NRG #40C. Accounting for the difference in frictional torque would result in a small but improved classification index.

IV. Results

Using the measured anemometer data as inputs, AnemCq6.exe, an executable Fortran code supplied by Troels Pedersen of DTU Wind Energy Department, was used to quantify the bounded errors and associated Classification Indices of the NRG Class 1 Anemometer. This is the same program that was used in the Accuwind study.

The bounded errors and associated Classification Indices of the NRG Class 1 Anemometers (S/N 047 and S/N 066) are shown in Figure 5 through Figure 8. Figure 5 and Figure 6 show the bounded errors and Classification Indices of the NRG Class 1 Anemometers subject to the Class A operational range of influence parameters. Figure 7 and Figure 8 show the bounded errors and Classification Indices of the NRG Class 1 Anemometers subject to the Class B operational range of influence parameters.

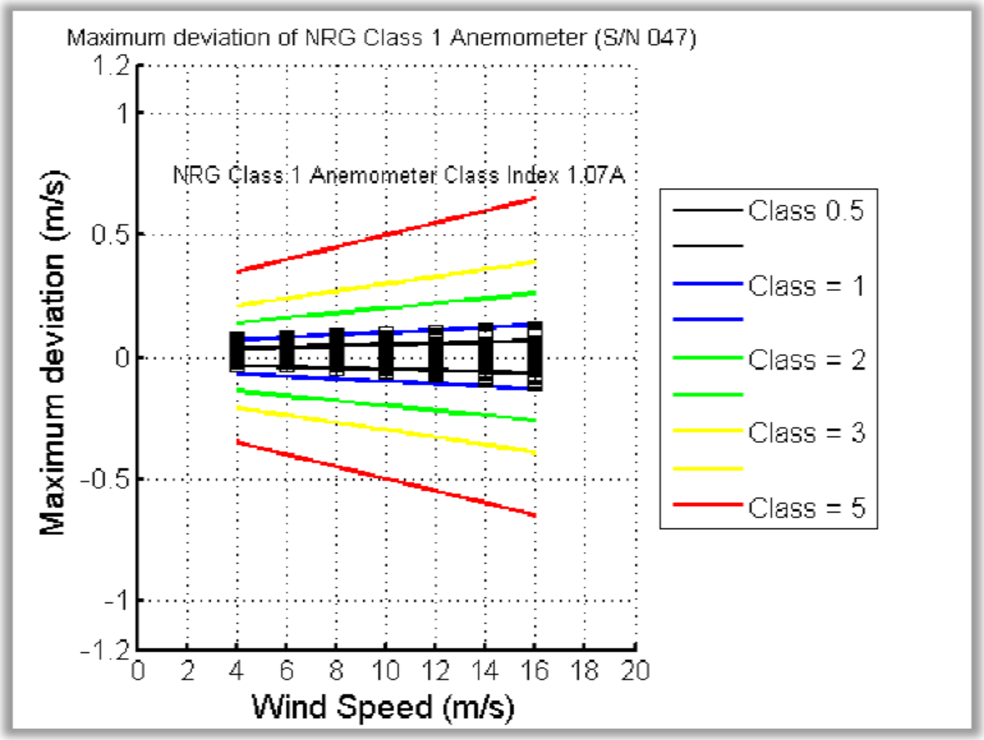

Figure 5 NRG Class 1 Anemometer (S/N 047) Maximum Deviations Class A

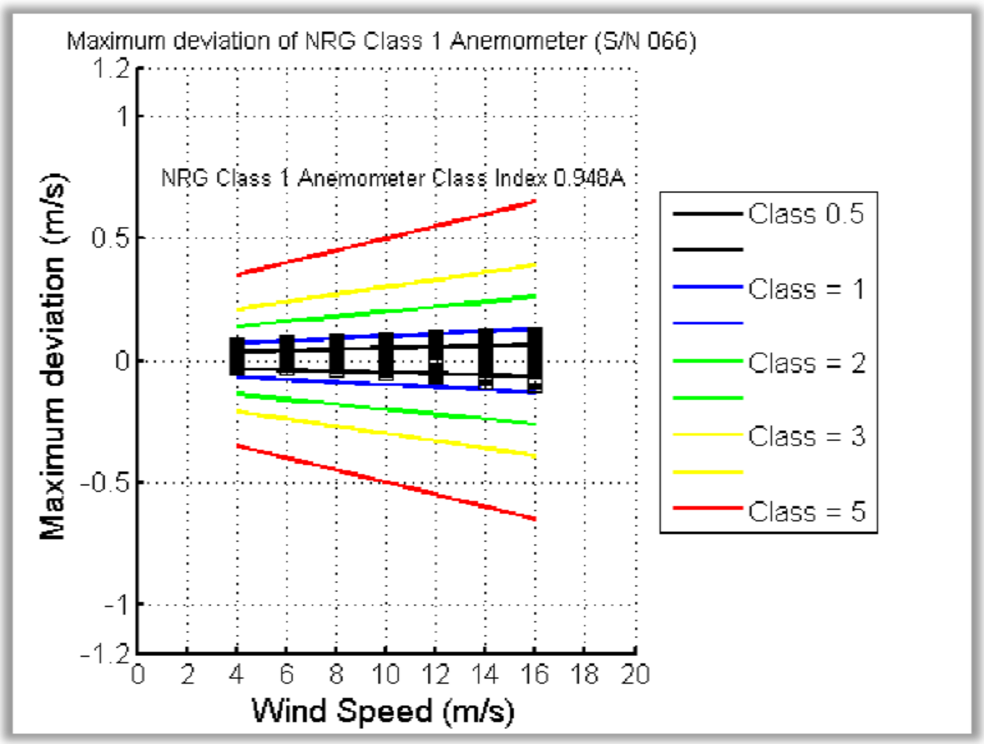

Figure 6 NRG Class 1 Anemometer (S/N 066) Maximum Deviations Class A

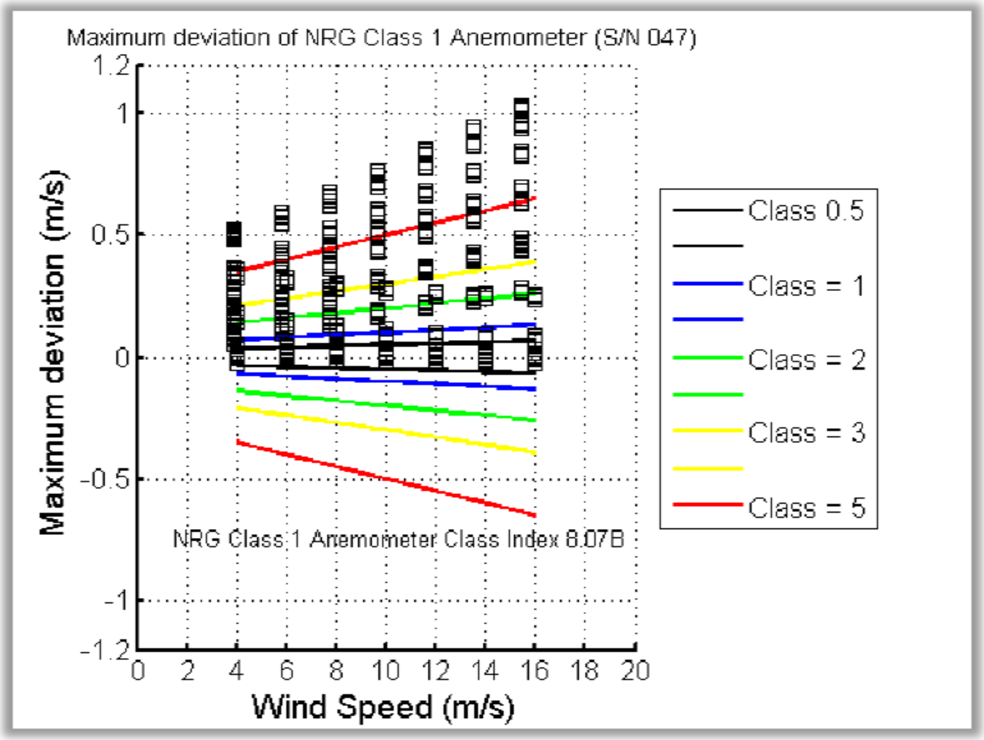

Figure 7 NRG Class 1 Anemometer (S/N 047) Maximum Deviations Class B

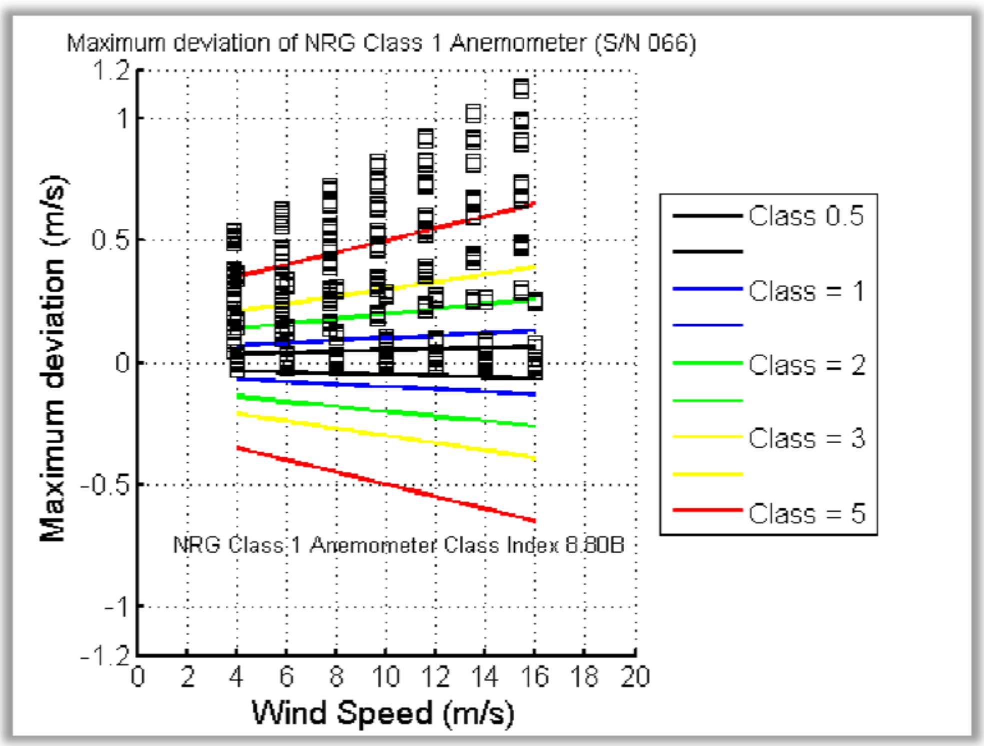

Figure 8 NRG Class 1 Anemometer (S/N 066) Maximum Deviations Class B

Per IEC 61400-12-1, Annex I of the Standard states, "At least two examples of a type of anemometer shall be assessed" for the classification of anemometry. In compliance with this requirement, two (2) NRG Class 1 Anemometers (S/N 047 and S/N 066) were characterized to determine the anemometer classification. The Classification Indices of two (2) NRG Class 1 Anemometers (S/N 047 and S/N 066) are reported in Table 4. The average Classification Indices of the NRG Class 1 Anemometer are 1.01A and 8.44B.

Table 4 Summary of Classification Indices for NRG Class 1 Anemometers

NRG Class 1 Anemometer S/N	Class A Index	Class B Index
S/N 047	1.07	8.07
S/N 066	0.948	8.80
Average Value	1.01	8.44

Troels Pedersen's letter certifying the classification of the NRG Class 1 Anemometer is included in the attachments.

V. References

IEC 61400-12-1 Power performance measurements of electricity producing wind turbines. Geneva: International Electrotechnical Commission (IEC).

J.-Å. Dahlberg, T. P. (May 2006). *ACCUWIND -Methods for Classification of Cup Anemometers (Risø-R-1555(EN)).* Denmark: DTU Wind Energy Dept (formerly RISO National Laboratory).

Pedersen, T. (2012, May). AnemCq6.exe: Fortran code used to calculate the Classification Index. Denmark.

T.F. Pedersen, J.-Å. D. (May 2006). *ACCUWIND -Classification of Five Cup Anemometers According to IEC61400-12-1 (Risø-R-1556(EN)).* Denmark: DTU Wind Energy Dept (formerly RISO National Laboratory).

VI. Attachments

Letter certifying classification of NRG Class 1 Anemometer

Risø DTU

DTU

NRG Systems, Inc.
110 Riggs Road
Hinesburg, Vermont 05461
USA
Attention: Mr Steve Clark

11 May 2012

Concerning endorsement of classification of NRG Class 1 Anemometer

I herewith confirm participation in consultative assistance (through conference calls and written correspondence) with NRG Systems, Inc. in order for the company to implement and operate the cup anemometer classification Fortran code Anemcq6 based on the ACCUWIND Classification Method .

Under my guidance NRG Systems, Inc. has characterized and classified the NRG Class 1 Anemometer (a ball bearing version of the NRG 40C anemometer) according to the ACCUWIND methods documented in the reports Risø-R-1555 and Risø-R-1556 and the IEC61400-12-1 standard annex I.

NRG Systems, Inc. has calibrated the test anemometers s/n 047 and s/n 066 in the SOH wind tunnel (MEASNET wind tunnel). Tilt responses of the cup anemometers were also measured in the SOH wind tunnel. Additionally, NRG Systems, Inc. performed bearing friction measurements on their cup anemometers with ball bearings in their own flywheel test climate chamber. Rotor torque and rotor inertia measurements were not made on the test anemometers. Rotor torque measurements were based on the original torque measurements made by FOI in the ACCUWIND project on the ACCUWIND NRG test anemometer, and were fitted to the ball bearing calibration conditions. Rotor inertia was based on the original rotor inertia measurement made by Risø in the ACCUWIND project on the same test anemometer. Data are presented in the NRG Systems, Inc. note: Characterization and Classification of the NRG Class 1 Anemometer for IEC61400-12-1 Compliance.

Following the ACCUWIND classification methods and the IEC61400-12-1 standard with the above derived data, the Classification Indices of the NRG Class 1 Anemometer were determined by NRG Systems, Inc. to be 1.07A and 8.07B and 0.948A and 8.80B, of the two cup anemometers respectively. The classification results were confirmed by my own calculations based on the same data. NRG Systems, Inc. combined the results and averaged the values to the final classification results 1.01A and 8.44B.

Sincerely

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NRGBBO-047.cup Input File

```
NRG BBO 40                                            Cup anemometer name ACCUWIND
0.070    0.00200   0.000101           2               R  Area  I  N(pulses/rev)
0.76572  0.19924   31.5         1.16                  Acal  Bcal  (U=Acal*f+Bcal)  Tcal   Denscal
0.1375                                                Ut
2                                                     Cup model (1 CqPol(Npol+alamQA0+pol-coeff) 2 CqTable(Ndata+lambda ver. Cq-coeff)
19       -0.0014                                      Ncq   LamCorr (model 2)  (added lambda0 value at zero torque)
0.2195846       0.4131825
0.2258573       0.383902
0.2336324       0.3334675
0.2431028       0.2781659
0.2545438       0.2032274
0.2662563       0.1249963
0.2788921       0.0342945
0.284611        0.0000000
0.2851037       -0.0029559
0.2919326       -0.0369015
0.3060246       -0.1173289
0.3229471       -0.2371572
0.343841        -0.3867344
0.3677941       -0.5398267
0.3986888       -0.7445405
0.4362507       -1.0651025
0.4839353       -1.3742118
0.5400939       -1.7541968
0.5898678       -2.1130812
8                                                     Ntemp No of temperatures
-30     0.3440E-04      0.0191E-04      -0.0001E-04
-20     0.2670E-04     0.0133E-04       -0.0000E-04
-10     0.2219E-04      0.0080E-04      -0.0000E-04
0       0.1985E-04      0.0055E-04      -0.0000E-04
10      0.1896E-04      0.0034E-04      -0.0000E-04
20      0.1824E-04      0.0024E-04      -0.0000E-04
30      0.1698E-04      0.0018E-04      -0.0000E-04
40      0.1622E-04      0.0014E-04      -0.0000E-04
27      7                                             SOH tilt data,     Nalfa  Valfa
-30.138 1.069
-26.153 1.045
-22.144 1.019
-18.121 0.992
-14.097 0.98
-10.087 0.982
-6.071  0.989
-4.033  0.991
-3.044  0.994
```

-2.027	0.997		
-1.014	0.997		
-0.016	0.999		
-0.013	1		
-0.009	0.999		
-0.002	1.001		
0.018	1.001		
1.024	1.001		
2.02	1.003		
3.031	1.005		
4.048	1.004		
6.054	1.001		
10.099	0.99		
14.142	0.991		
18.168	1.008		
22.187	1.043		
26.209	1.06		
30.144	1.043		
27	10	Nalfa	Valfa
-30.138	1.072		
-26.153	1.049		
-22.144	1.022		
-18.121	0.994		
-14.097	0.979		
-10.087	0.98		
-6.071	0.988		
-4.033	0.991		
-3.044	0.993		
-2.027	0.997		
-1.014	0.998		
-0.016	0.999		
-0.013	1		
-0.009	1		
-0.002	1.001		
0.018	1.001		
1.024	1.001		
2.02	1.004		
3.031	1.005		
4.048	1.005		
6.054	1.002		
10.099	0.99		
14.142	0.992		
18.168	1.006		
22.187	1.037		
26.209	1.055		
30.144	1.042		

27	13	Nalfa	Valfa
-30.138	1.074		
-26.153	1.051		
-22.144	1.023		
-18.121	0.996		
-14.097	0.978		
-10.087	0.98		
-6.071	0.987		
-4.033	0.991		
-3.044	0.992		
-2.027	0.996		
-1.014	0.999		
-0.016	0.999		
-0.013	0.999		
-0.009	1		
-0.002	1.001		
0.018	1.001		
1.024	1.002		
2.02	1.005		
3.031	1.006		
4.048	1.006		
6.054	1.002		
10.099	0.991		
14.142	0.993		
18.168	1.005		
22.187	1.034		
26.209	1.053		
30.144	1.042		

NRGBBO-066.cup Input File

NRG BBO 40				Cup anemometer name ACCUWIND
0.070	0.00200	0.000101	2	R Area I N(pulses/rev)
0.76645	0.20439	31.7	1.16	Acal Bcal (U=Acal*f+Bcal) Tcal Denscal
0.15				Ut
2				Cup model (1 CqPol(Npol+alamQA0+pol-coeff) 2 CqTable(Ndata+lambda ver. Cq-coeff)
19	-0.001			Ncq LamCorr (model 2) (added lambda0 value at zero torque)
0.2195846	0.4131825			
0.2258573	0.383902			
0.2336324	0.3334675			
0.2431028	0.2781659			
0.2545438	0.2032274			
0.2662563	0.1249963			
0.2788921	0.0342945			
0.284611	0.0000000			
0.2851037	-0.0029559			
0.2919326	-0.0369015			
0.3060246	-0.1173289			
0.3229471	-0.2371572			
0.343841	-0.3867344			
0.3677941	-0.5398267			
0.3986888	-0.7445405			
0.4362507	-1.0651025			
0.4839353	-1.3742118			
0.5400939	-1.7541968			
0.5898678	-2.1130812			
8				Ntemp No of temperatures
-30	0.3445E-04	0.0154E-04	-0.0000E-04	
-20	0.3011E-04	0.0084E-04	-0.0000E-04	
-10	0.2637E-04	0.0051E-04	-0.0000E-04	
0	0.2400E-04	0.0034E-04	-0.0000E-04	
10	0.2219E-04	0.0023E-04	-0.0000E-04	
20	0.2081E-04	0.0019E-04	-0.0000E-04	
30	0.2000E-04	0.0015E-04	-0.0000E-04	
40	0.1919E-04	0.0011E-04	-0.0000E-04	
27	7			SOH Tilt Data Nalfa Valfa
-30.148	1.079			
-26.154	1.053			
-22.13	1.023			
-18.108	0.996			
-14.088	0.982			
-10.085	0.982			
-6.071	0.991			
-4.041	0.995			
-3.044	0.997			

-2.032	0.998
-1.012	0.998
-0.009	1
-0.006	0.999
-0.005	1
0.002	1
0.005	1
1.02	1.002
2.018	1.003
3.013	1.004
4.031	1.004
6.059	1.001
10.09	0.99
14.133	0.994
18.169	1.014
22.166	1.054
26.176	1.073
30.125	1.06
27	10
-30.148	1.083
-26.154	1.057
-22.13	1.028
-18.108	0.998
-14.088	0.981
-10.085	0.982
-6.071	0.989
-4.041	0.994
-3.044	0.996
-2.032	0.997
-1.012	0.998
-0.009	1
-0.006	1
-0.005	1
0.002	0.999
0.005	1.001
1.02	1.002
2.018	1.004
3.013	1.005
4.031	1.005
6.059	1.002
10.09	0.992
14.133	0.993
18.169	1.011
22.166	1.049
26.176	1.071
30.125	1.067

27	13
-30.148	1.085
-26.154	1.058
-22.13	1.03
-18.108	0.999
-14.088	0.98
-10.085	0.981
-6.071	0.987
-4.041	0.993
-3.044	0.995
-2.032	0.996
-1.012	0.998
-0.009	1
-0.006	1
-0.005	1.001
0.002	0.999
0.005	1.001
1.02	1.003
2.018	1.004
3.013	1.005
4.031	1.005
6.059	1.003
10.09	0.992
14.133	0.993
18.169	1.009
22.166	1.047
26.176	1.07
30.125	1.071