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OPTIMAT BLADES
NEW WISPER RANGE PAIR- BENCHMARKING

Conclusions 1st round

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1 NEW WISPER Range Pair - Benchmarking

1.1 General

To verify the compatibility of the **Annual-Range-Pair** and **Low-Cycle-Fatique** derivation technique of the partners participating in TG1 WP 4 *NEW WISPER* a benchmark exercise is carried out. Sample data supplied by DEWI are evaluated on the basis of:

- Bernard Bulder - ECN, Denja Lekou, Pantelis Vionis - CRES Rogier P.L. Nijssen - TUDelft, Theo Kramkowski, Holger Söker - DEWI: SYNTHESIS PROCESS OF A NEW WISPER LOAD SPECTRUM. DEWI, 27.10.2003, Wilhelmshaven

In the described benchmark exercise the sample data set is to be processed using the above mentioned synthesis procedure. In this procedure Rainflow counting is applied on the data. The participating partners are requested to specify the software routines :

- ***DEWI:*** IMC COM Software Package COM/Klass-D V.1 Rev. 4 used in evaluation procedures for time series measurements. This software uses Rainflow counting according to ASTM E1049-85 (reapproved 1990), *Standard Analysis*.
- ***CRES: :*** CRES in house developed software is used in evaluation for time series measurements. The software uses Rainflow counting algorithm as described in IEA "Recommended practices for wind turbine testing and evaluation; 3 Fatigue loads" (Edition 1990), following IEC 61400-13 "Measurement of Mechanical Loads" (Edition 1998).
  Since the algorithm is half-cycle counting the sample data (in particular the residuals after the range pair extraction), sequence is to be Rainflow counted and the result shall be presented in half cycle matrices as well as range spectra.
- ***ECN:*** In house developed software Rainflow and Rainmtrx. Rainflow performes rainflow counting of time series according to *Recommended practices for wind turbine testing and evaluation; 3. Fatigue* . In Rainmtrx the range mean matrix and the range spectra are generated using the Rainflow results as input.

The annual Range Pair is to be derived from sample data and extrapolated to one year following the above quoted procedure and bullet 1.4. Subsequently normalisation of cyclic content (rotational speed) shall be carried out evaluating the number of cumulated rotor revolutions from the edgewise range pair spectrum. The number of revolutions is to be taken from the bin in which the second derivation of the range pair spectrum envelope is zero (approached from large loads to small loads). The normalization factor is found by relating the reference no of revolutions to the counted number of revolutions per year:

factor = ref. no. of revolutions / no of counted revolutions

As last step in this benchmark the Low-Cycle-Fatique values are be added as described in the “A simple approximative procedcure for taking into account low cycle fatique loads” by G.Larsen and K.Thomsen Ris∅ National Laboratory, Roskilde, Denmark January 1996.
The result shall be presented in a full cycle flatwise matrix as well as a flatwise range-pair spectrum. From the range pair spectrum the 1-Hz-EQL value are to be derived. Range pair spectra and EQLs are to be grouped in an Excel sheet for ready access.

1.2 Sample Data

The sample data are characterized as follows:

- data files (edge- and flatwise bending) for 12% turbulence intensity are sorted in wind bins from V03 (3m/s) up to V25 (25m/s) (normalized data!)
- a single start and stop data file are given in corresponding directories
- each sample data set contains 30000 data points i.e. 600s duration at sample rate of 50 Hz as typically recorded during load measurements

1.3 Rainflow Counting Parameters

To perform the rainflow count on the sample data parameters are set to:

RAINFLOW COUNTING PARAMETERS	edgewise
No of Bins, evenly devided	64
Full Scale Minimum	-2
Full Scale Maximum	2
Hysteresis (110% of Bin Width)	0.0688
Treatment of Residuals 1 = each residual transition from one load level to another is added as a full cycle to the rain flow full cycle matrix 0 = residual transition from one load level to another are neglected	1

Tab. 1. Rainflow Counting Parameter *edgewise*

RAINFLOW COUNTING PARAMETERS	flatwise
No of Bins, evenly devided	64
Full Scale Minimum	-2
Full Scale Maximum	6
Hysteresis (110% of Bin Width)	0.1375
Treatment of Residuals 1 = each residual transition from one load level to another is added as a full cycle to the rain flow full cycle matrix 0 = residual transition from one load level to another are neglected	1

Tab. 2. Rainflow Counting Parameter *flatwise*

note: The rainflow counting parameters for CRES are different from the ones described in the above two tables only in the Hysteresis part, for which CRES uses a Threshold set equal to 5% of Bin width, i.e. 0.003125 for the edgewise loads and 0.00625 for the flatwise loading.

1.4 Range Pair Spectrum Parameters

To compute the annual range pair spectrum the following parameters are specified:

ANNUAL RANGE PAIR PARAMETERS	
Weibull Parameters	A= 9.52 C= 2.0
V_cut in	3 m/s
V_cut out	22 m/s
Low Cycle Fatigue considered	yes

Tab. 3. Annual Range Pair Parameter *A-Parameter must be 9.59 which was in fact used by ECN and DEWI*

For the low cycle fatigue portion the delivered annual wind speed time series is to be evaluated according to

- Larsen, G.; Thomsen, K.: A simple approximative procedure for taking into account low cycle fatigue loads. Paper presented at IEA-Symposium on Wind Turbine Fatigue, Stuttgart, February 1-2, 1996

The used numbers of starts and stops or transients at Cut-in and Cut-out wind speed are to be reported:

Definitions:

- start at cut in: whenever the 10-min-average wind speed chages from below 3m/s to above 3m/s
- start at cut out: whenever the 10-min-average wind speed chages from above 22m/s to below 22m/s
- stop at cut in: whenever the 10-min-average wind speed chages from above 3m/s to below 3m/s
- stop at cut out: whenever the 10-min-average wind speed chages from below 22m/s to above 22m/s

1.5 Equivalent Load Parameters

To compute the equivalent load from the Rainflow range pair spectra the following parameters are specified:

EQUIVALENT LOAD PARAMETERS	
No of Bins (i)	64
N_{ref} = Number of equivalent load cycles	31536000
M = material exponent	10
Formula used	$L_{eq} = \left(\frac{\sum n_i * L_i^m}{N_{ref}} \right)^{(1/m)}$

Tab. 4a. Equivalent Load Parameter

EQUIVALENT LOAD PARAMETERS used by CRES	
No of Bins (i)	64
N_{ref} = Number of equivalent load cycles	31536000
m = material exponent	10
Formula used where L_i is taken as the upper bound of each bin	$L_{eq} = \left(\frac{\sum n_i L_i^m}{2N_{ref}} \right)^{1/m}$

Tab. 4b. Equivalent Load Parameter *used for CRES*

For the material constant a value of 10 shall be evaluated. The number of equivalent load cycles is assumed to be 31536000. As the spectra represent a total of 1 one year the computed EQL corresponds to the 1Hz-EQL.

1.6 Overall Results

The results of the benchmark exercise are presented in the following.

STATISTICS OF STARTS AND STOPS ACCORDING TO LCF				
	CRES	DEWI	ECN	
Starts cut-in	Appr. 400	404	268	
Starts cut-out	n.a.	17	7	
Stops cut-in	Appr. 400	404	268	
Stops cut-out	n.a.	17	7	
	level crossing analysis, no hysteresis applied	level crossing analysis, no hysteresis applied	rainflow analysis, no hysteresis applied, bin mid at 1,2, 3m/s etc	

Table 5: Statistics of starts and stops according to annual wind speed time history

NORMALIZATION OF CYCLIC CONTENT						
ref. Rpm	20					
min/year	525600					
ref. No. of rev.	10512000					
	DEWI	ECN	CRES			
Bin	30					
Counts	8376277.8	12972000				
mean rpm	15.936602	24.680365				
Factor	**1.2549727**	**0.8103608**				
1/factor	0.7968301	1.2340183				
Note! The normalization factor is to be carried out before adding the LCF-cycles !						

Table 6: NORMALIZATION OF CYCLIC CONTENT

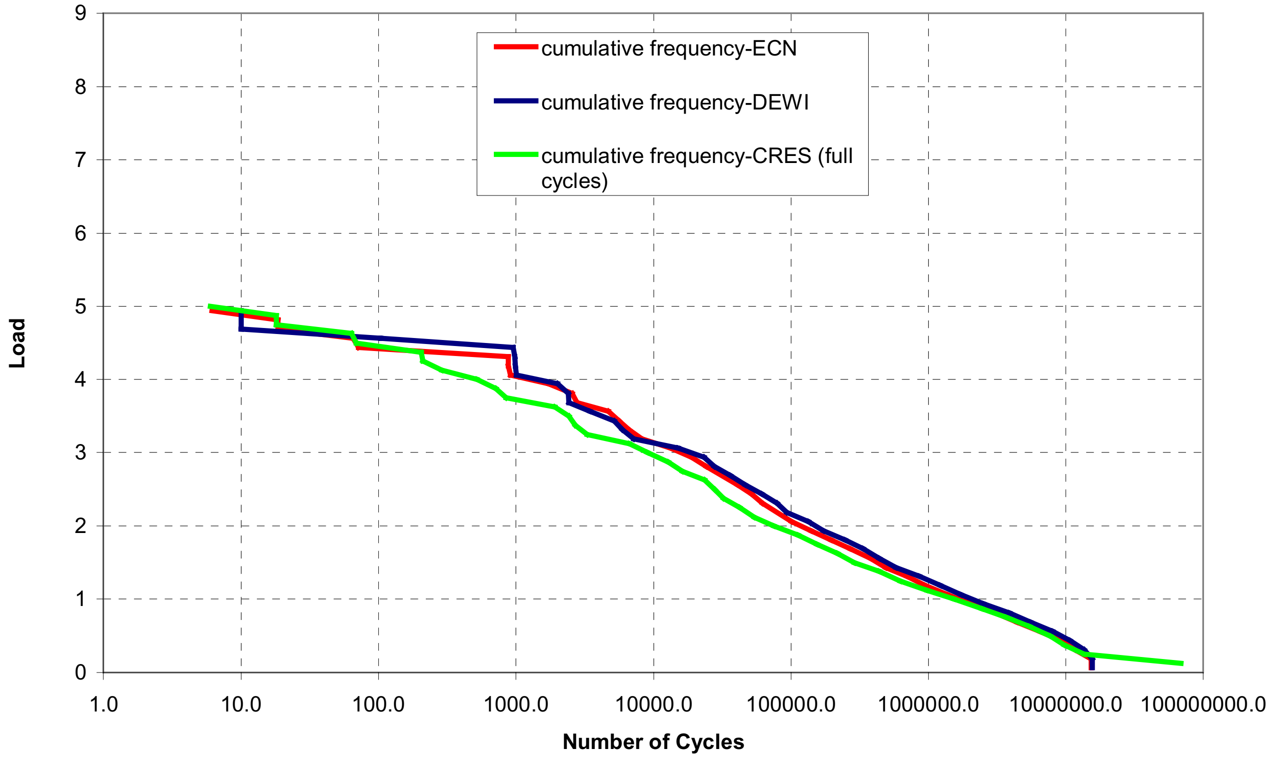

Fig. 1: Normalized Flatwise Range-Pair Spectrum and 1-Hz EQL

Partner	CRES	DEWI	ECN	ECN-computed by DEWI
Material exponent	10	10	10	10
EQL	1.576	1.716	1.905	1.692

Table 7: 1Hz-EQL Results

1.6.1 Results From DEWI

Table 8 gives the normalized flatwise annual range pair spectrum obtained from the sample data set:

Range Pair Spectrum flatwise	DEWI		
Bin	Load in i-th Bin	Cumulative frequency	counts
1	0.0625	15631471,2	0,0
2	0.1875	15631471,2	2021890,2
3	0.3125	13609581,0	2875355,0
4	0.4375	10734226,0	2639367,4
5	0.5625	8094858,6	2560728,6
6	0.6875	5534130,0	1630495,6
7	0.8125	3903634,3	1373183,2
8	0.9375	2530451,1	808621,9
9	1.0625	1721829,2	494798,0
10	1.1875	1227031,3	374502,3
11	1.3125	852528,9	270828,1
12	1.4375	581700,8	140772,0
13	1.5625	440928,9	104979,3
14	1.6875	335949,6	86913,4
15	1.8125	249036,1	75565,4
16	1.9375	173470,8	38952,3
17	2.0625	134518,5	41474,2
18	2.1875	93044,2	13496,4
19	2.3125	79547,8	18080,0
20	2.4375	61467,9	15046,8
21	2.5625	46421,1	10037,8
22	2.6875	36383,3	8670,8
23	2.8125	27712,6	4347,9
24	2.9375	23364,7	8268,9
25	3.0625	15095,8	7902,4
26	3.1875	7193,4	1264,7
27	3.3125	5928,7	760,9
28	3.4375	5167,8	1718,6
29	3.5625	3449,2	1035,3
30	3.6875	2414,0	24,0
31	3.8125	2390,0	381,6
32	3.9375	2008,3	994,7
33	4.0625	1013,7	25,0
34	4.1875	988,7	6,0
35	4.3125	982,7	26,0
36	4.4375	956,7	852,7
37	4.5625	104,0	94,0

38	4.6875	10,0	0,0
39	4.8125	10,0	0,0
40	4.9375	10,0	10,0
41	5.0625	0	0
--			
64	7.9375	0	0

Table 8: DEWI Range-Pair Spectrum Numbers changed to comply with overall result 1/12/2005

Figure 2 depicts the range pair spectrum (cumulative frequency of counted rainflow cycles) as obtained by using the IMC COM Software Package COM/Klass-D V.1 Rev. 4.

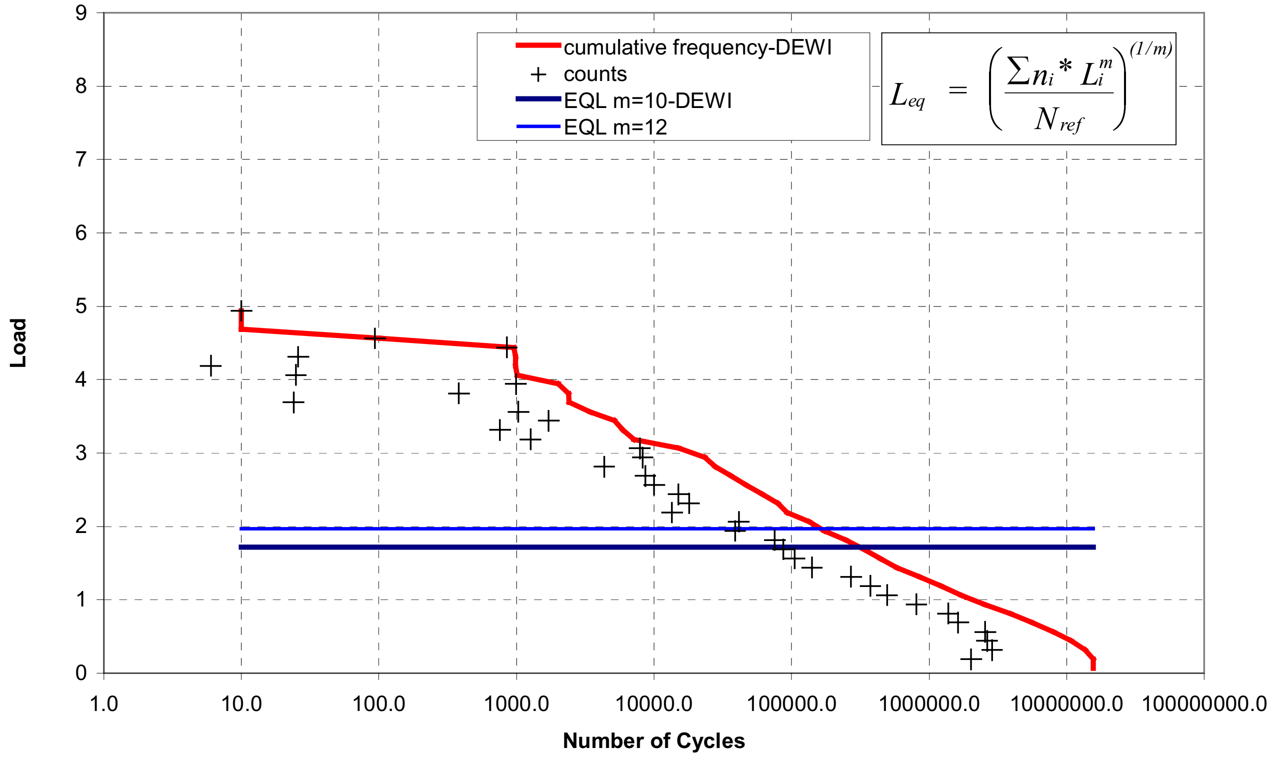

Fig. 2: DEWI's Normalized Flatwise Range-Pair Spectrum and 1-Hz EQL

material exponent m	3	4	6	8	10	12
equiv. No. of cycles	31536000	31536000	31536000	31536000	31536000	31536000
EQL	0,65067	0,80691	1,12696	1,43582	1,71634	1,96448

Table 9: DEWI'S 1Hz-EQL Results Numbers changed to comply with overall result 1/12/2005

1.6.2 Results From CRES

Following table (Table 10) gives the range spectrum for the flatwise loading obtained from the Rainflow matrix. The matrix data includes the residual counts. Rainflow counting matrix has been obtained by an in-house built software using the algorithm described in previous section of this document. In the appendix CRES' rainflow half cycle matrix in Range – Mean representation is listed in tabular format.

Range Pair Spectrum FLATWISE			
Bin	Load in i-th Bin	Cumulative frequency	half cycle counts
1	0.125	137636831	110417649
2	0.25	27219182	7713038
3	0.375	19506144	3945787
4	0.5	15560357	4601948
5	0.625	10958409	3603862
6	0.75	7354547	2424810
7	0.875	4929737	1872370
8	1	3057367	1109696
9	1.125	1947671	692504
10	1.25	1255167	371183
11	1.375	883984	306543
12	1.5	577441	139178
13	1.625	438263	129192
14	1.75	309071	84745
15	1.875	224326	74194
16	2	150132	41366
17	2.125	108766	24298
18	2.25	84468	19597
19	2.375	64871	8874
20	2.5	55997	8888
21	2.625	47109	14631
22	2.75	32478	6916
23	2.875	25562	7499
24	3	18063	4680
25	3.125	13383	6765
26	3.25	6618	1214
27	3.375	5404	556
28	3.5	4848	1019
29	3.625	3829	2130
30	3.75	1699	270
31	3.875	1429	393
32	4	1036	459
33	4.125	577	154
34	4.25	423	14
35	4.375	409	271
36	4.5	138	10
37	4.625	128	92
38	4.75	36	0
39	4.875	36	24
40	5	12	12

Table 10: CRES Range Spectrum for flatwise load

Figure 3 depicts the range spectrum (cumulative frequency of counted rainflow half cycles) as obtained by using the software built by CRES using the algorithm described in previous section of this document.

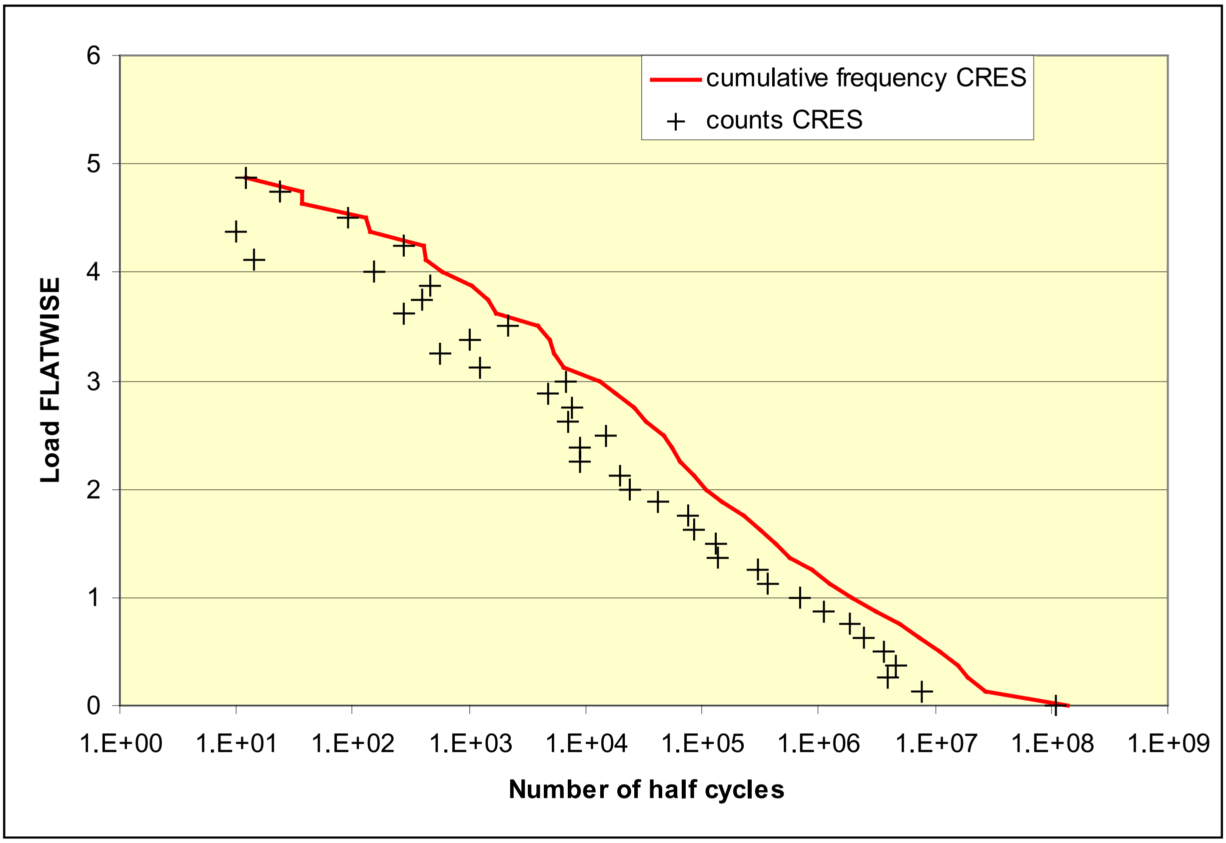

Fig. 3: CRES' Range Spectrum and 1-Hz EQL of Flatwise loads

Material exponent m	4	6	8	**10**	12
Equiv. No. of cycles	31536000	31536000	31536000	**31536000**	31536000
EQL - Flatwise	0.715	1.011	1.306	**1.576**	1.816
EQL - Edgewise	1.744	1.958	2.088	**2.184**	2.264

Table 11: CRES 1Hz- EQL Results

NOTE: No normalization for the cyclic content (rotational speed) has been made for deriving the above results.

1.6.3 Results From ECN

The table below shows the flatwise load spectrum.

bin	number of occurences	load
1	1	5.938
2	1	5.813
3	1	5.688
4	1	5.563
5	1	5.438
6	1	5.313
7	1	5.188
8	1	5.063
9	7	4.938
10	20	4.813
11	20	4.688
12	67	4.563
13	73	4.438
14	876	4.313
15	885	4.188
16	911	4.063
17	1723	3.938
18	2559	3.813
19	2765	3.688
20	4700	3.563
21	5646	3.438
22	6592	3.313
23	8217	3.188
24	13269	3.063
25	18957	2.938
26	24357	2.813
27	31555	2.688
28	41040	2.563
29	51579	2.438
30	62028	2.313
31	78832	2.188
32	101828	2.063
33	140293	1.938
34	195836	1.813
35	268666	1.688
36	379825	1.563
37	493180	1.438

38	698493	1.313
39	952660	1.188
40	1373072	1.063
41	2036100	0.938
42	3085000	0.813
43	4430307	0.688
44	6475909	0.563
45	9262281	0.438
46	11645011	0.313
47	15325046	0.188
48	15325046	0.063
49	15325046	0.000
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64	15325046	0.000

Table 12 ECN Range Pair Spectrum

The 1 Hz equivalent flatwise load is 1.905 with material constant m = 10.

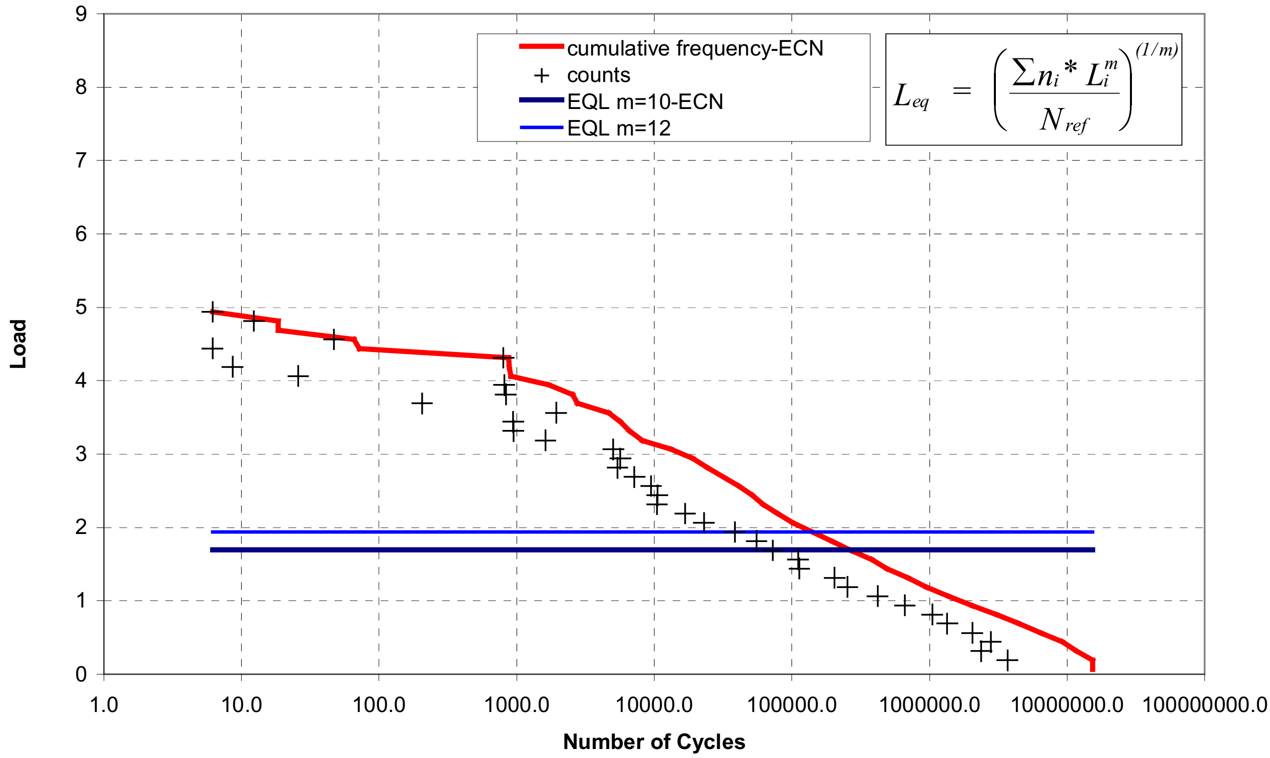

Fig. 4: ECN's Normalized Flatwise Range-Pair Spectrum and 1-Hz EQL

The 1 Hz equivalent flatwise load is 1.905 with material constant m = 10.

Note: DEWI has recomputed EQL with ECN's range pair spectrum and obtained the following values:

material exponent m	3	4	6	8	10	12
equiv. No. of cycles	31536000	31536000	31536000	31536000	31536000	31536000
EQL	0.6088	0.7694	1.0991	1.4131	1.6919	1.9336

Table 9: 1Hz-EQL Results based on ECN's range pair spectrum recomputed by DEWI

1.7 CONCLUSION

We have found rather large differences in the annual rage pair benchmark exercise. In the following find the most relevant observations:

- Applied hysteresis of only 5% in rainflow counting for CRES does not comply with specified benchmark parameters – can this be changed?

- ECN and DEWI used the IEC class II Weibull distribution specified for the benchmark (A=9.59, C=2). CRES used the wind speed distribution given by the annual wind speed time series – all partners used IEC class II.

- Normalization for cyclic content is rather complicated to explain: it is intended to find the number of revolutions on the almost vertical drop of the cumulative edgewise range pair spectrum (y-axis = load, x-axis = counts). The definition used above refers to the phenomenon that the curvature of the cumulative spectrum-curve changes its sign on the vertical drop section: coming from high loads the cumulative spectrum-curve increases its slope bending right (downwards) until the maximum slope is reached – then the slope will decrease again with the cumulative spectrum-curve bending left (towards horizontal direction). The number of counts shall be taken from the load bin in which the curvature changes sign i.e. second derivation is zero. As there may be several such points we suggest to choose the first bin coming from larger loads.

  DEWI and ECN have selected quite different bins and hence reference numbers of revolutions. CRES has not carried out normalization

  ECN: For the normalization of the cyclic content ECN took the wrong number of revolutions. Now we find 0.82792 E7, resulting in a factor f = 1.270. The slope of cumulative spectrum-curve goes from zero to steepdown = negative and goes to zero again. this means that the second derivative is never zero. DEWI: We do not agree! When the slope (i.e. first derivative) of the cumulative spectrum-curve has a local minimum then the derivative of this slope (I.e. the second derivative) must be zero in the point with the steepest drop of the cumulative spectrum-curve.

  The definition of the factor is not used identically. For clarity it shall be :

  factor= reference annual rotor revolutions/ annual no. of rotor revolutions

  Applying the correct definition would have given in case of ECN a factor of 0.8103. However, choosing a much higher no of actual revolutions and using the reversed normalization factor produced a very similar number of total counts in the DEWI and ECN spectra.

  Note: The definition of the factor is by fault reversed in the NEW WISPER Synthesis Document!! This has been mentioned in the remarks document circled a few weeks ago.

  All partners shall use the formula stated above with a reference rotor speed of 20 rpm.

- Treatment of residuals is not unique! CRES keeps half cyles, DEWI uses ful cycles (as suggested in the benchmark specs), For full cycle counts the residu is handled by ECN as follows. Depending which has the largest range, the even or odd single ranges are counted as full cycles. As a consequence ECN and CRES only count half as many "residual-full-cycles"
All partners shall use full cycles for all residual load transitions.

- The number of starts and stops assumed by the partners in analysing the annual wind speed time series is rather different.

  ECN: To determine number of starts and stops at cut in 3 m/s and cut out 22 m/s ECN applied a rainflow count. According to ECN this is the correct procedure. The rainflowcount is performed with and without a hysteresis of 110% of binwidth. The binwidth was selected 1 m/s. The bin_mids were selected 0.5, 1.5, 2.5 etc. and 1, 2, 3 etc. This resulted in different counts in the from-to matrix. For cut-in the number of start and stops are given below:

	bin_mids 1, 2, 3 etc	bin_mids 0.5, 1.5, 2.5 etc.
no hysteresis	268	397
110 % hysteresis	179	264

  What is the bin_mid to be selected and is hysteresis included? We should agree on the bin_mid and the hysteresis. ECN suggests bin_mids 0.5 etc and hysteresis included.

  CRES has reported (oral information) some 400 starts and 400 stops with no hysteresis considered.

  DEWI has counted level crossings on the wind speed time history before binning and obtained some 404 starts and 404 stops. As we are looking at 10-min-averages of wind speed it can be realistically assumed that the turbine has actually started or stopped when passing the threshold.

  Conclusion: All partners shall adopt the procedure of level crossing counting for the cut-in and cut out wind speeds without hysteresis (best before binning to avoid discretization problems – otherwise binning shall be chosen in a way that the *cut-in* threshhold falls on a bin border) . In case of the given anual wind speed time series this results in 404 starts and 404 stops at cut-in and 17 starts and 17 stops at cut-out wind speed.

  ECN: Above cut-out 25 m/s the turbine will stop, but this thus does not mean that a turbine starts when the windspeed is below cut out. The turbine ECN uses will start again when the wind is below 20 m/s. Should the lowcycle count be turbine specific? DEWI: If such behaviour is known for the used wind turbine such behaviour shall be considered. The number of starts/stops/transients is anyhow turbine dependent due to varying cut out wind speeds. Also transients from one to another generator stage is turbine dependent and shall be treated (and reported) anlogous to the starting and stopping.

- ECN's computed EQL's are differing – when recomputed by DEWI's formulation the difference has almost vanished. ECN should check-up on the used formula. In the MEASNET exercise we did not find so large differences – please correct!

1.8 CONTACT

In case of questions or support is needed turn to

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