OPTIMAT BLADES

TASK GROUP 1 – WP4

NEW WISPER

Creating a New Standard Load Sequence From Modern Wind Turbine Data

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1 EXECUTIVE SUMMARY

Sixteen years back a load sequence for variable amplitude testing of materials in wind energy applications has been defined. The sequence has been synthesized from the measured flatwise blade root bending loads of 9 wind turbines varying from18 kW to 3 MW in power and from 12 m to 100 m in diameter. Very different operating philosophies have been covered. This load sequence called WISPER has found international acceptance and is widely used in variable amplitude testing of wind turbine rotor blade materials. In the context of the EU-co-funded OPTIMAT BLADES project [1] that aims at optimizing materials and design recommendations for wind turbine rotor blade it has been proposed to set up a NEW WISPER standard load sequence that reflects today's state-of-the-art in wind energy conversion technology. The idea is that material characteristics like fatigue life limits can be provided with better confidence for use in modern wind turbine rotor blade design when a test sequence reflecting today's turbine technology is used to establish such characteristics.
Following this line of thinking a work group within the OPTIMAT BLADES project has been formed to work out a NEW WISPER standard load sequence. The work group consisting of CRES, ECN, DEWI, DLR and WMC represents considerable experience in the field of wind turbine load determination and material testing. The report presents the major issues that have been discussed when creating NEW WISPER. The final resulting NEW WISPER sequence is presented and compared to the old WISPER standard sequence. The comparison is carried out on the basis of the rainflow range pair load spectra, 1-Hz equivalent load calculations and even more complex damage calculations using GFRP-material Goodman-diagrams and advanced damage accumulation models.

1.1 Task Group 1 Description

Investigation of blade material behaviour under variable amplitude loading.
Task Group Leader: Christoph Kensche, DLR
WP3: Variable Amplitude Fatigue Loading
WP4: Establishment of New WISPER Spectrum
WP5: Interactions with Variable Amplitude loading

1.2 Work Package 4 Description

Work package No : **WP4**								
Work package title:	**ESTABLISHMENT OF NEW WISPER SPECTRUM**							
	Work package leader:	DLR						
Participant:	ECN	TUDT	DLR	DEWI	CRES			
Person-months per participant:	4	3	6	4	3			

Objectives:
To define a new standard load spectrum, based on the size and use of contemporary large wind turbines and compare the results of this to the present spectrum.

Description of work:

Task 4.1. DPA - Definition and collection of blade spectra
Set-up of criteria for acceptance and normalisation of available load measurement data and specification of a common data format for further processing and preparation of 10 data bases.
The load spectrum assembly method will be defined and applied for assembly of a flap wise load spectrum for each data base for a selected turbulence level and a selected wind distribution. The assembly for all data bases will be performed by TUDT. This task will be co-ordinated by DEWI, supported by data from ECN and CRES.

Task 4.2: Synthesis of spectra to NEW WISPER
The assembled measured load spectra are compared to the WISPER standard through fatigue life estimation on the basis of the constant amplitude properties and the linear Palmgren-Miner damage accumulation theory. From this the NEW WISPER spectrum will be established. All partners.

Task 4.3: Experimental validation of the NEW WISPER
Variable amplitude tests will be accomplished with NEW WISPER on the reference material. Similar to the tests described in WP 3.4 with WISPER, the influence of omission will be investigated for the NEW WISPER spectrum. The tests will be carried out by DLR, TUDT and CRES.

Task 4.4: Evaluation of variable amplitude influence
The results of Tasks 4.1 to 4.3 will be compared to the results of the constant amplitude tests and the tests with the WISPER spectrum (both WP3). This must be performed also analytically by lifetime prediction on the basis of both the WISPER standard and the NEW WISPER. Then, the difference of the test results and the prediction have to be compared. All partners.

Deliverables:

15 Description of NEW WISPER standard load spectrum (report)
16 Validation report of NEW WISPER

Milestones and expected results:

M3 DPA on NEW WISPER
M11 Evaluated influence variable amplitude effect

1.3 Work Package 4 Participants

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2 VARIABLE AMPLITUDE LOADING

Variable amplitude testing is considered to be absolutely necessary as simple S-N curves (based on constant amplitude and R-ratio) insufficiently represent the interactions of large and small cycles in a realistic type of loading: when testing a specimen using the known **WISPER** load sequence (**WI**nd **SPE**ctrum **R**eference) the number of load cycles (of varying amplitude) to failure for a given maximum strain level are considerably larger than for constant amplitude and R-ratio tests (see Fig. 1).

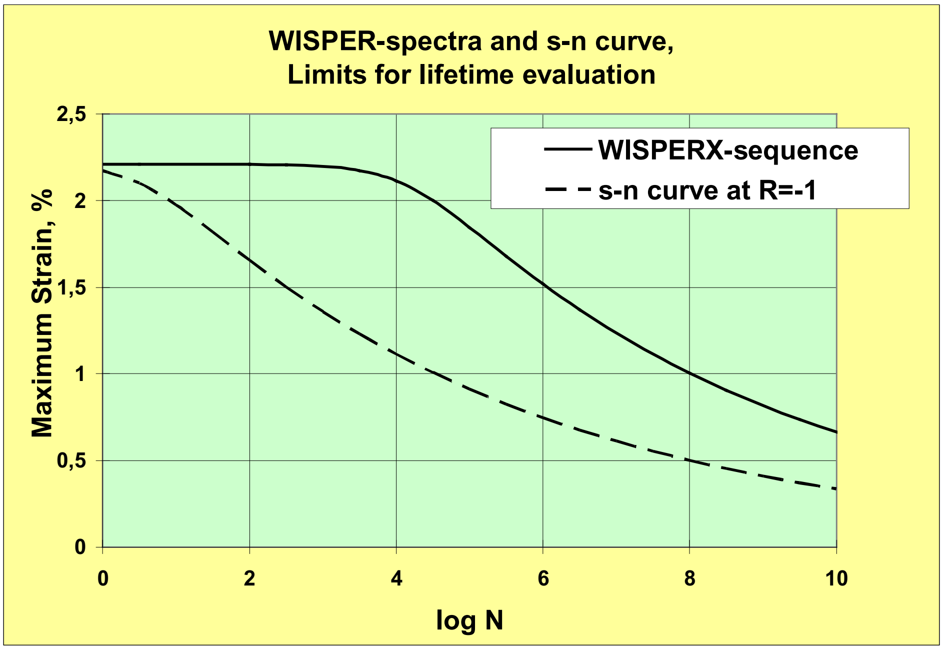


Fig.1: Number of Cycles to Failure for Variable Amplitude (WISPERX) and Constant Amplitude and R-Ratio Testing

With respect to variable amplitude loading the OPTIMAT BLADES task group 1 has benchmarked the individual lifetime prediction methods used by the project partners for composite materials. In a second step a reference material for the actual testing work has been selected and characterized on basis of S-N curves. In a next step the reference material is tested with the known **WISPER** sequence. In a further set of experiments the newly developed **NEW WISPER** sequence is applied to the test specimen. And the results from the experiments (**WISPER** and **NEW WISPER**) will be compared to the life time predictions based on damage calculations. This analysis is deemed to give valuable input to the process of design guideline formulation.

Test sequences like **WISPER** have been developed in other industries as well. Especially in aircraft industries the idea of standard load sequences is widely accepted as can be taken from the following examples:

HELIX/FELIX:	Helicopters
TWIST:	Transport Aircraft
FALSTAF:	Military Aircraft
KoSMOS:	Light Aircraft/Sailplanes
WISPER	Wind energy

3 WISPER VS NEW WISPER

The **WI**nd **SPE**ctrum **R**eference has been established by an IEA work group some 15 years ago [2]. It was based on measurements on 9 wind turbines of sizes between 11.7 m and 100 m, with blades of steel, GFRP, wood. The “dead” sequence holds 132.711 cycles in 64 load levels and is applied as a standard for comparison of materials and lifetime estimations in wind energy context. It has been derived from the flatwise rotor blade bending moments measured on several wind turbines. The WISPER sequence is largely accepted and is used by material testing laboratories, industry and the research community for comparisons of experimental and life time prediction results.

As WISPER comes of age and has been based on wind turbine technology of the early days the OPTIMAT BLADES consortium felt it was time for a NEW WISPER standard sequence that shall refer to the actual loads on today’s large rotor blades that are designed with composite material blades and that are operated with modern control mechanisms. The vast majority of today’s MW and Multi-MW scale turbines use full span pitch control and variable speed operating schemes. Also load measurements are more easily available and the data volumes being at hand are a multiple of those available in the days of creating WISPER.

The characteristics of the NEW WISPER sequence are:

- 8 turbines out which 6 are of MW or MMW -scale
- rotor diameters between 37m and > 100m
- rotor blades made of composites
- 6 turbines pitch controlled / 2 turbines stall controlled
- 5 turbines with variable speed / 3 with two fixed speeds
- all turbines 3-bladed

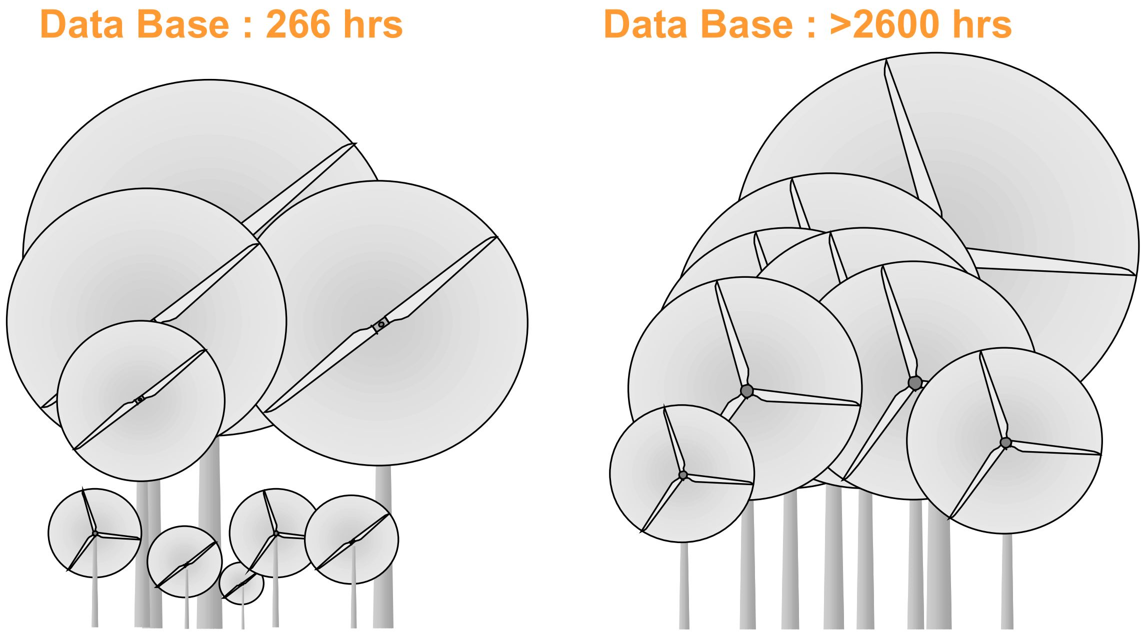


Fig. 2 : WISPER and NEW WISPER Turbines – Visual Comparison of Turbines Delivering Data

4 THE MAKING OF NEW WISPER

In the following the process of *“the making of **NEW WISPER**”* is described. Generally, standard techniques according to IEC 61400-13 have been applied in order to achieve simplicity and transparency of the process and to maintain confidentiality of data. The data were taken from commercial blade load measurements after permission had been acquired from the industrial parties owning them. In 8 easy steps the **NEW WISPER** standard load sequence for flatwise blade bending has been formed. But before **NEW WISPER** could be established some things had to be learned from **WISPER**.

4.1 Recovery and Adaptation of WISPER Synthesis

All partners of Work Package were requested to assess the procedure used to establish the old WISPER load standard as laid out in the comprehensive report by Ten Have NLR in 1992 [1]. In this assessment needs for adaptation of the process to today’s engineering requirements and to today's wind energy technology standard were compiled in the list below

Pos.	Originator	Step	Description	Decision
1	TUD	Format	NEW WISPER shall have the same format as that of the old WISPER/X i.e. a fixed sequence of load reversal points on a discrete amount of levels	Agreed – Methodology of how to derive the fixed sequence to be adapted
2	ECN	Rainflow Counting	64 load level shall be maintained	Agreed
3	ECN	Input (Load) data	Flapwise or flatwise bending i.e shall the pitch angle be considered or not	Flatwise bending moments are to be considered i.e. within the blade coordinate system – no consideration of pitch angle required.
4	TUD	Rainflow Counting / Data Handling	Data handling according to IEA recommendations on fatigue assessment to be checked	All partners have participated in a rainflow benchmarking: techniques are reasonably well aligned to have each partner use their own rainflow counting procedures.
5	TUD	Wind data	Wind and load data shall originate from the same measurements	Discarded: wind speed distribution shall be common to all data bases and wind turbulence levels are to be selected for each data base individually to achieve best possible coverage of wind speed spectrum.
6	DEWI	Wind data	Shall a the assembly process assume an IEC class 1 wind distribution	Wind speed distribution shall be common to all data bases: either IEC class 1 / 2 or according to a real year long measurement (can data from NLR exercise be recovered?)
7	DEWI	Wind data	Shall the “low cycle” fatigue approach i.e. sequential selection of per-operation-mode-load-matrices according to a sequence of 10-minute wind speed averages. Shall / can we obtain this sequence from NLR Alternative: go through wind speed distribution bin by bin and linearly extrapolate the per-bin-load-rainflow-matrix	In addition to the bin by bin linear superposition and extrapolation of the binwise load rainflow matrices the low cycle approach according to IEC 61400-13 (Appendix) shall be applied. (see procedure outline below)

8	TUD	Input (Load) data	Use of computer simulations to obtain load data for a large variety of design solutions (e.g. turbine concept, # of blades...) and external / operation characteristics (e.g. complex terrain-, wind farm-, offshore- operation)	Use of computer simulated loads has been discarded in the second meeting June 2002 at RISO
9	TUD / ECN	Input (Load) data	Necessity to incorporate edgewise loading	Incorporation of edgewise loading discarded can better be addressed in static amplitude tests
10	DEWI	Normalisation level	Shall the normalization scheme be preserved (normalization by “once-per-1000-rev. Level”)? Should we normalize with respect to power (e.g. by span of average loads at 20% and 80% of rated power)	A normalization scheme using span of average loads at 20% and 80% of rated power has been suggested (see below)
11	DEWI	Truncation and Omission	Truncation and omission practice to be confirmed	Matter of actual synthesis: truncation most likely does not apply , omission will be necessary to cut down on cyclic content of the rainflow counts
12	DEWI	Reduction of cyclic content	Procedure is somewhat unclear at this point	To be

Table1: Work Group Inputs And The Decisions Met on The Individual Issues

4.2 *NEW WISPER Synthesis Procedure*

The base line for the set up of a new procedure for a **NEW WISPER** test load sequence is threefold:

- Standard techniques as used by the participating partners and laid out in the existing standards (here IEC 61400-13) shall be used to make use of best and established practice and to ensure acceptability in the wind turbine industry.
- Simplicity and transparency of the synthesis process shall be achieved.
- In order to maintain confidentiality of the data used the participating work group members shall supply processed data only.

The following outlines the suggested synthesis process in detail:

4.2.1 STEP 1: Turbine / Site Description & Data Selection (Per Turbine):

Turbine and site had to be described according to an agreed anonymous format. The data available had to be reported in capture matrices according to IEC 61400-13. For each individual capture matrix the data of the turbulence bin with widest coverage of wind speed bins had to be chosen together with those in the turbulence bin above and below. This ensures a sufficiently large data base. Lacking data at the high wind speed end had to be substituted either with data sets of the required wind speed but with turbulence out of the selected range or the data set with the largest available wind speed had to be used in the lacking bins up to cut out wind speed.

The turbine represented in the data bases used are described by the following parameters:

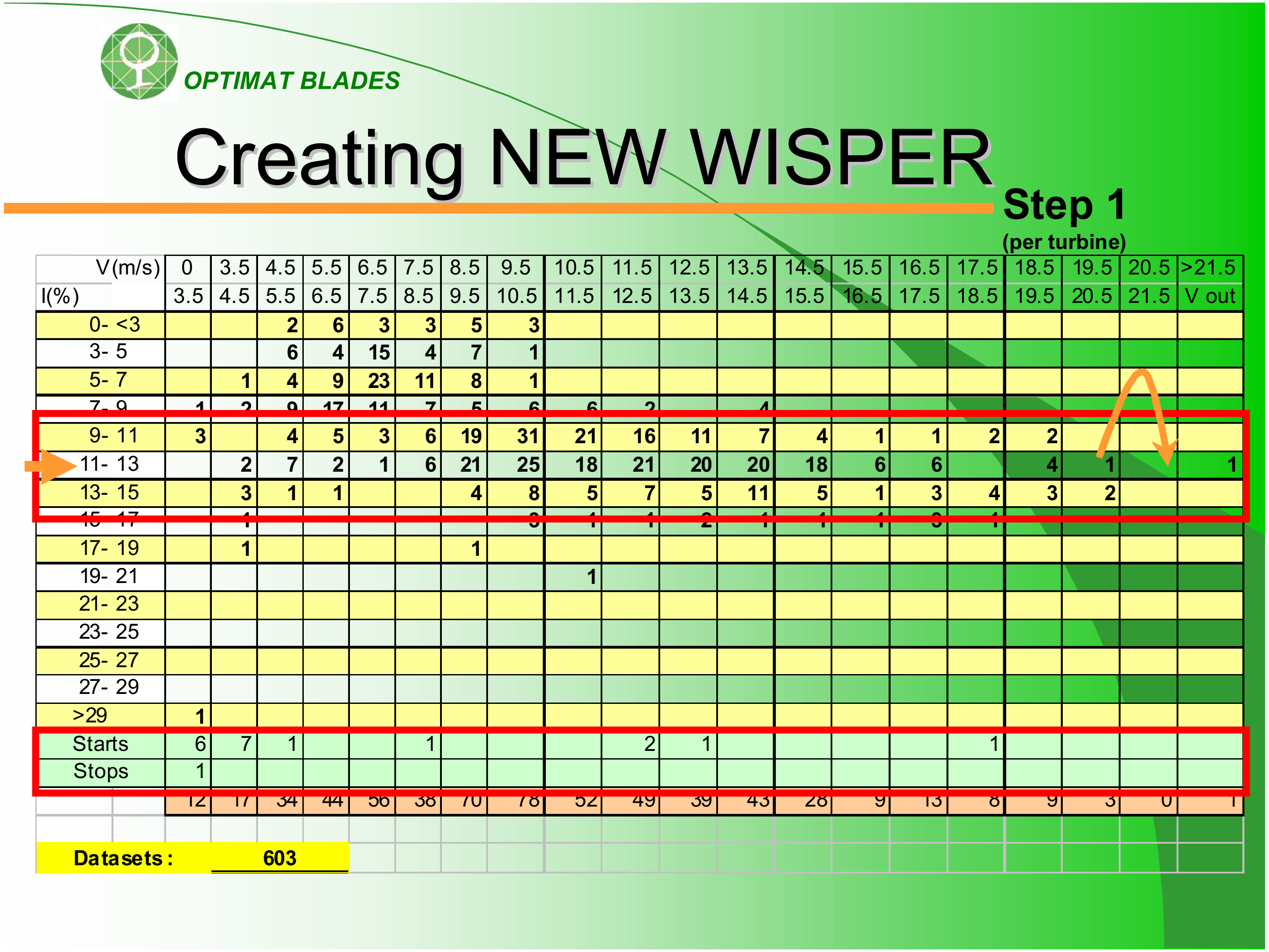
- Rotor diameter
- Rated power
- Power control
- Rotor speed, maximum (two speeds?, speed range)
- No. of blades
- Rotor position (upwind / downwind)
- Hub height
- Prototype / serial production turbine

The site represented in the data bases used are described by the following parameters:

- Topography
- Sector of load measurements
- Mean turbulence in sector

The data base had to be given by a IEC 61400-13 capture matrices of 10-Min time histories for normal power production and transient operation. The subsequent steps were taken:

- Pick turbulence bin with the widest wind speed coverage.
- Add data of turbulence bin above and below, resulting in a turbulence bin of 6% width.
- Substitute missing data from other turbulence bins and report such substitution.
- Copy data from highest wind speed bin up to the 25m/s bin.
- Identify / select representative transients of starts and stops at cut in and cut-out (above rated) wind speed.
- Identify / select representative transients of rotor speed switching (low to high / high to low rpm) if applicable.



OPTIMAT BLADES

Creating NEW WISPER

Step 1
(per turbine)

V(m/s)	0	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	>21.5
I(%)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5	V out
0- <3			**2**	**6**	**3**	**3**	**5**	**3**												
3- 5			**6**	**4**	**15**	**4**	**7**	**1**												
5- 7		**1**	**4**	**9**	**23**	**11**	**8**	**1**												
7- 9	**1**	**2**	**9**	**17**	**11**	**7**	**5**	**6**	**6**	**2**		**4**								
9- 11	**3**		**4**	**5**	**3**	**6**	**19**	**31**	**21**	**16**	**11**	**7**	**4**	**1**	**1**	**2**	**2**			
11- 13		**2**	**7**	**2**	**1**	**6**	**21**	**25**	**18**	**21**	**20**	**20**	**18**	**6**	**6**		**4**	**1**		**1**
13- 15		**3**	**1**	**1**			**4**	**8**	**5**	**7**	**5**	**11**	**5**	**1**	**3**	**4**	**3**	**2**		
15- 17		**1**						**3**	**1**	**1**	**2**	**1**	**1**	**1**	**3**	**1**				
17- 19		**1**					**1**													
19- 21									**1**											
21- 23																				
23- 25																				
25- 27																				
27- 29																				
>29	**1**																			
Starts	6	7	1			1				2	1					1				
Stops	1																			
	12	17	34	44	56	38	70	78	52	49	39	43	28	9	13	8	9	3	0	1

Datasets : 603

Fig. 3 Data Selection Scheme from Capture Matrix

4.2.2 STEP 2: Normalization of Flatwise Bending (Per Turbine):

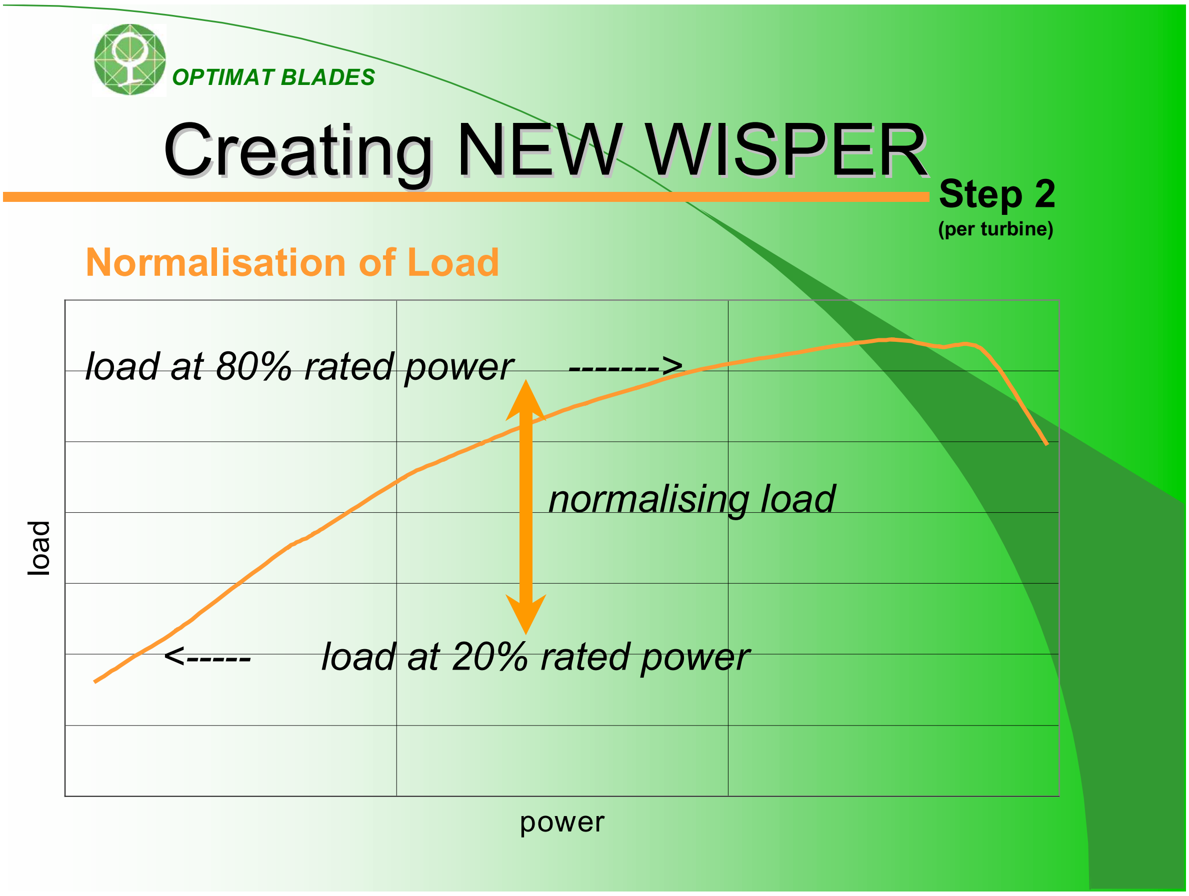
In order to be able to combine the loads measured on various machines with different designs a normalization of the load level is required. Such normalizing of the flatwise blade bending has been carried out following the bullets below:

- Derive wind speeds at 20% and 80% rated power from bin averaged power curve through interpolation. Determine the difference in the bin averaged mean flatwise bending at the above wind speeds by interpolating in the bin averaged flatwise load vs. wind speed curve.
- Alternatively: Determine the difference in the bin averaged mean flatwise bending at 20% and 80% power output by interpolating in the bin averaged flatwise load vs. electrical power output curve.
- Normalize all flatwise and edgewise bending loads by the above difference.
- The normalized maximum and minimum values of instantaneous flatwise loads (normal power production or transient operation) had to be reported.

The largest values of *all* turbines were used to set the limits for the Rainflow counting into a 64 x 64-bin-matrix. The reported normalized minima and maxima were:

CRES min : -1 max: +6
ECN min: -2 max: +4
DEWI min: -3 max: +5

Hence the range was chosen to minimum: -3 and maximum: +6.



OPTIMAT BLADES

Creating NEW WISPER

Step 2
(per turbine)

Normalisation of Load

Fig. 4: Normalization of Load level

4.2.3 STEP 3: Annual Cumulated Rainflow Load Spectrum (Per Turbine)

Using the selected data an annual cumulated Rainflow load spectrum had to be created for flatwise and edgewise blade bending. This load spectrum had to be derived for IEC wind turbine class II conditions i. e. Weibull- wind speed distribution with A= 9.59 C=2.0. In this context operation in each wind speed bin is regarded as an individual load case just as transient maneuvers.
Using the IEC class II wind speed histogram the load spectra for the individual machines were derived by each data supplying partner:

- Rainflow count each flatwise and edgewise data set and add up cycles for each wind speed bin. Rainflow parameters were defined mutually in the work group as follows:

RAINFLOW COUNTING PARAMETERS	flatwise
No of Bins, evenly divided	64
Full Scale Minimum	-3
Full Scale Maximum	6
Hysteresis (110% of Bin Width)	0.15469
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*

- Extrapolate load cycles of each wind speed bin according to the agreed on wind distribution to give cumulative duration of one year .
- Set up the annual flatwise and edgewise range / mean full cycle load matrix and cumulated range spectrum.

Note: to ensure that the data preparing partners are applying comparable rainflow counting tools a benchmark exercise [5] has been executed before the actual data processing that has be carried out by each data delivering partner on his own data base [see annex]. The benchmark exercise revealed some minor differences in the produced range pair spectra. It was concluded that the results were reasonably equal. The exact rainflow counter used in by the partners are specified in the benchmark document.

4.2.4 STEP 4: Normalization of Cyclic Content (Rotational Speed) (Per Turbine):

As all machines have different rotor speeds and the occurrence of some loading phenomena are known to be dependent on the rotational frequency a normalization of the cyclic content of the Rainflow load spectra was considered necessary. To do so the counts in the Rainflow matrix were to be scaled by a factor acquired by the reference number of revolutions for one year constant operation at 16 rpm divided by the actual annual number of revolutions. It must be noted here that the old WISPER standard employed a reference rotor speed of 45 rpm!

Normalization for cyclic content has been done as follows:

- Derive number of rotor revolutions per year from the cumulated edgewise range spectrum.
- As a *reference constant rotor speed 16rpm* have been defined in the group.
- Normalize Rainflow counts by the factor: reference annual rotor revolutions/ annual no. of rotor revolutions

4.2.5 STEP 5: Add low cycle loads for each turbine (IEC / RISOE proposal) and transient loads (Per Turbine):

Additional to step 3 an annual time series of 10-min-average wind speeds corresponding to the wind speed distribution of step 3 had to be applied for determination of the frequencies of transients and the load cycles arising from transitions from one load case to another. *Note: In this context operation in each wind speed bin is regarded as an individual load case just as transient maneuvers.*

The annual 10-min-average wind speed sequence was taken from DEWI's wind speed measurements on a 130m-meteorological tower near the coast of Lower Saxony. The Low Cycle Fatigue loading was modeled according to the RISØ-method discussed in detail in [4].

For determination of the number of starts /stops / transients (all partners):

- The number of starts, stops and rotor speed transients had to be derived from one year wind speed time history using peak/trough or level crossing counting and establishing a wind speed transition / level crossing from - to - matrix from that one year wind speed time history. The level crossing counting for the cut-in and cut out wind speeds should be done without hysteresis best before binning to avoid quantization problems – otherwise binning had to be chosen in a way that the *cut-in* threshold falls on a bin border.

The number of starts and stops used for an individual data base is dependent on cut-in and cut-out wind speed of the individual turbine and hence are reported by the processing partner (see annex Data Base Descriptions)

To account for the low cycle fatigue loading the IEC / RISOE approach is adopted:

- Arrange a sequence of maximum and minimum normalized flatwise loads according to one year wind speed time history. For each 10 minute interval throughout one year the maximum and minimum normalized flatwise loads of all load time histories in the respective wind speed bin are to be selected and added to a sequence.
- Rainflow count the above sequence into a range / mean full cycle load matrix (using the Rainflow parameters as selected for step 3.
- Add cycles to normalized annual flatwise Rainflow matrix
- Rainflow count the selected start / stop / rotor rpm transients into a range / mean full cycle load matrix (using the Rainflow parameters as selected for step 3
  The number of starts and stops to be used must be taken from the exercise described in the first bullet of this step.

- Rainflow count the selected emergency stop transients into a range / mean full cycle load matrix (using the Rainflow parameters as selected for step 1.2.6.). *The number of emergency stops per year to be considered has mutually been defined to be 40.*
- Add Rainflow counted cycles of the above no. of starts, stops and rotor rpm transients per year to above matrix

4.2.6 STEP 6: Compose flatwise Rainflow sum matrix of all turbines (DEWI)

In this step the flatwise blade bending Rainflow Load Matrices have been merged to blend into an averaged **NEW WISPER** load matrix. This step is performed rather straight forward through summation of the individual RFL matrices and subsequent division of the matrix elements (counts) by the number of turbines. The resulting rainflow range mean matrix can be seen in Fig. 5 while Fig. 6 shows the individual normalized rainflow range pair spectra and the combined range pair spectrum.

While all spectra run into a maximum number of cycles between 10 and 20 million their shape and maximum range level differ considerably. The overall maximum range level fell onto the border of bins 46 and 47. The range mean rainflow matrix shows a distinct double peak caused by equally distinct wind turbine technologies: variable speed pitch controlled machines and fixed speed stall controlled machines. Nevertheless, it has been decide to keep all eight turbines in the NEW WISPER synthetic load spectrum.

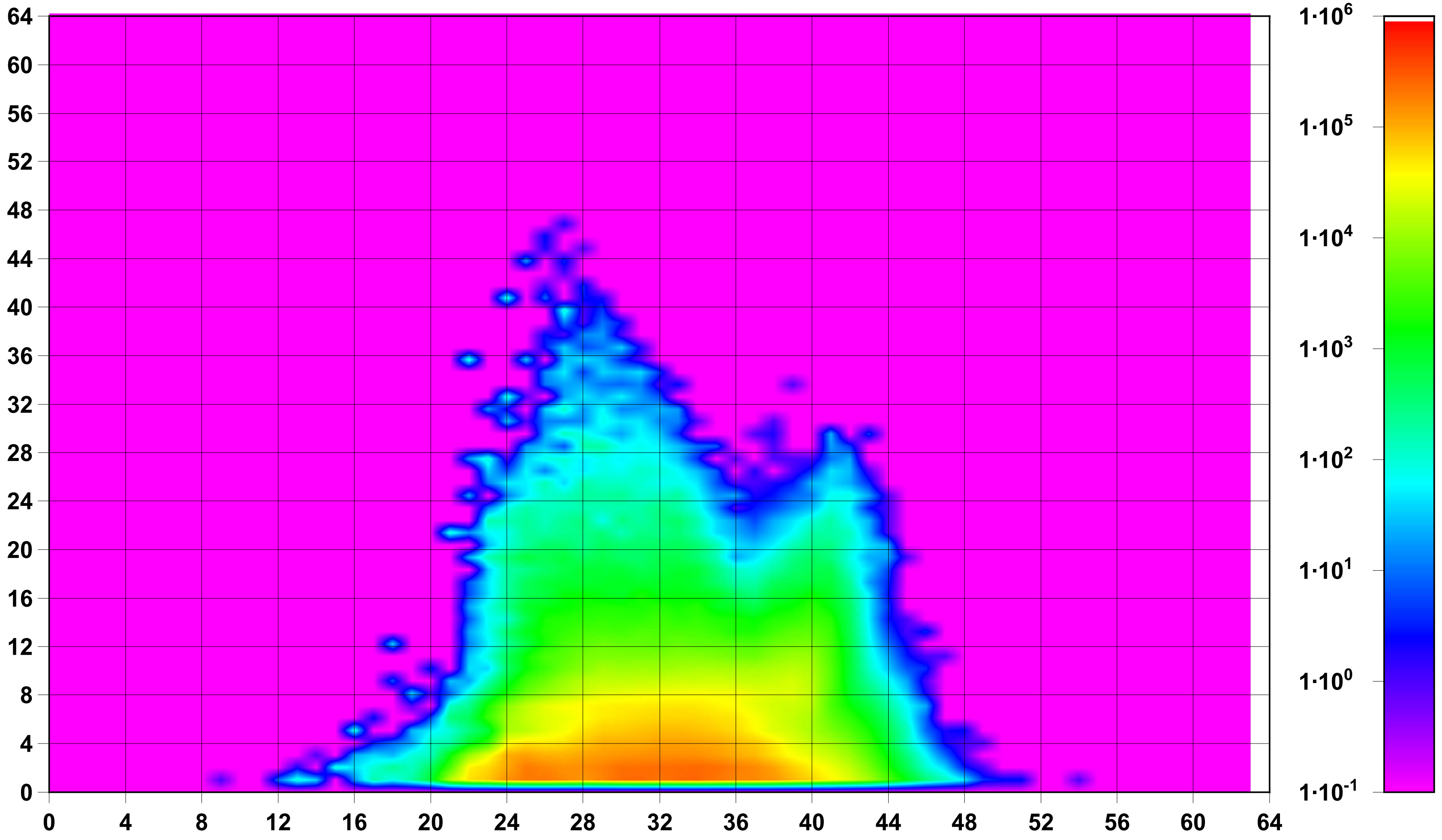


Fig. 5 : NEW WISPER Range Mean Rainflow Matrix – Average of All Examined Turbine

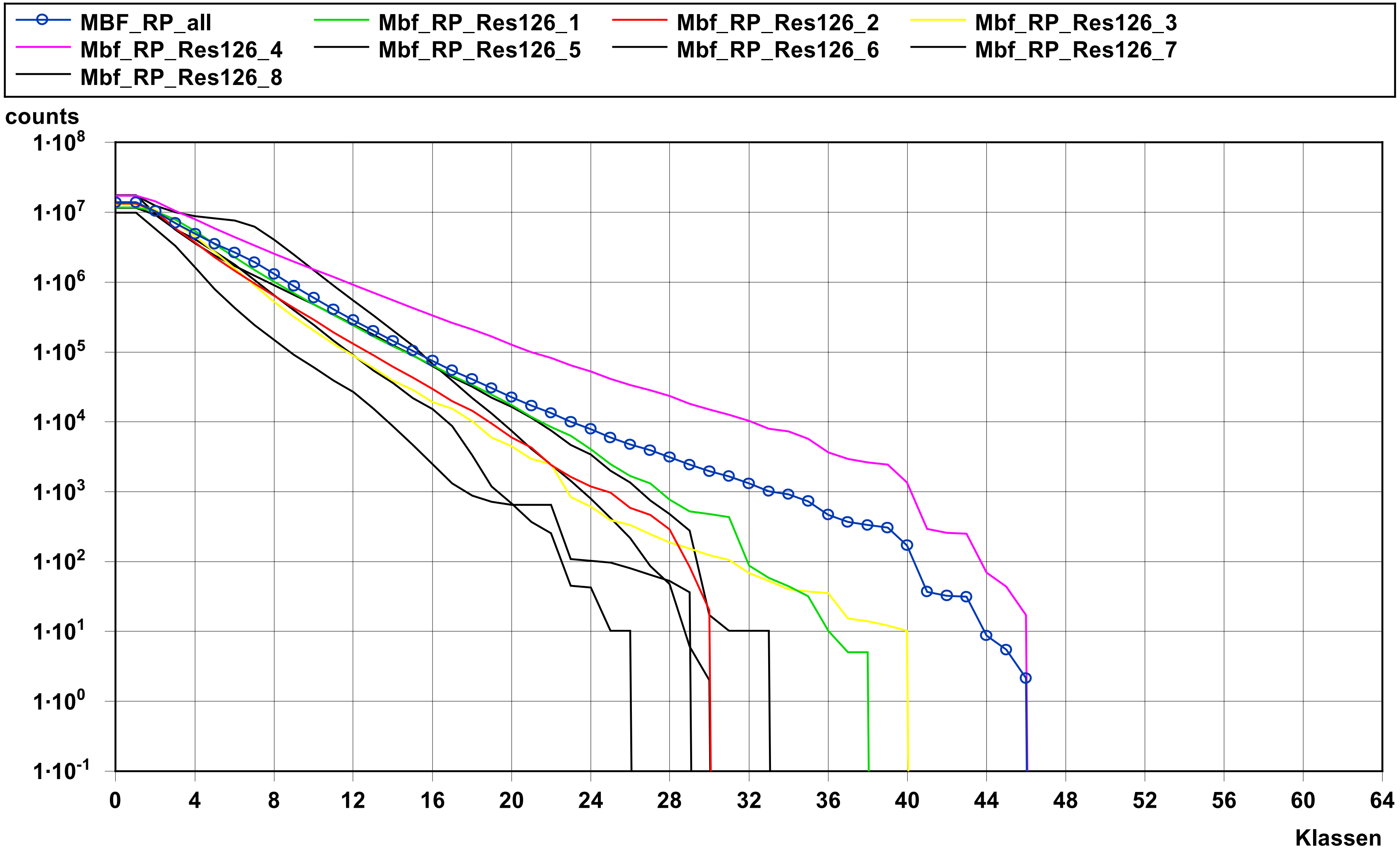


Fig. 6: NEW WISPER Range Pair Spectra for the Individual Turbines and Combined NEW WISPER SPECTRUM

4.2.7 STEP 7: Omission and Reduction (DEWI)

For better comparison a further step has to be taken: Omission (= leaving out the smallest load cycles with load ranges below a defined threshold) was applied to the **NEW WISPER** spectrum at 18.75 % of the maximum range. This level has been chosen to correspond to the 18.46% omission used for **WISPER**. Also following the role model the number of cycles within the **NEW WIPSER** sequence was reduced by a factor of 6. No truncation was applied.

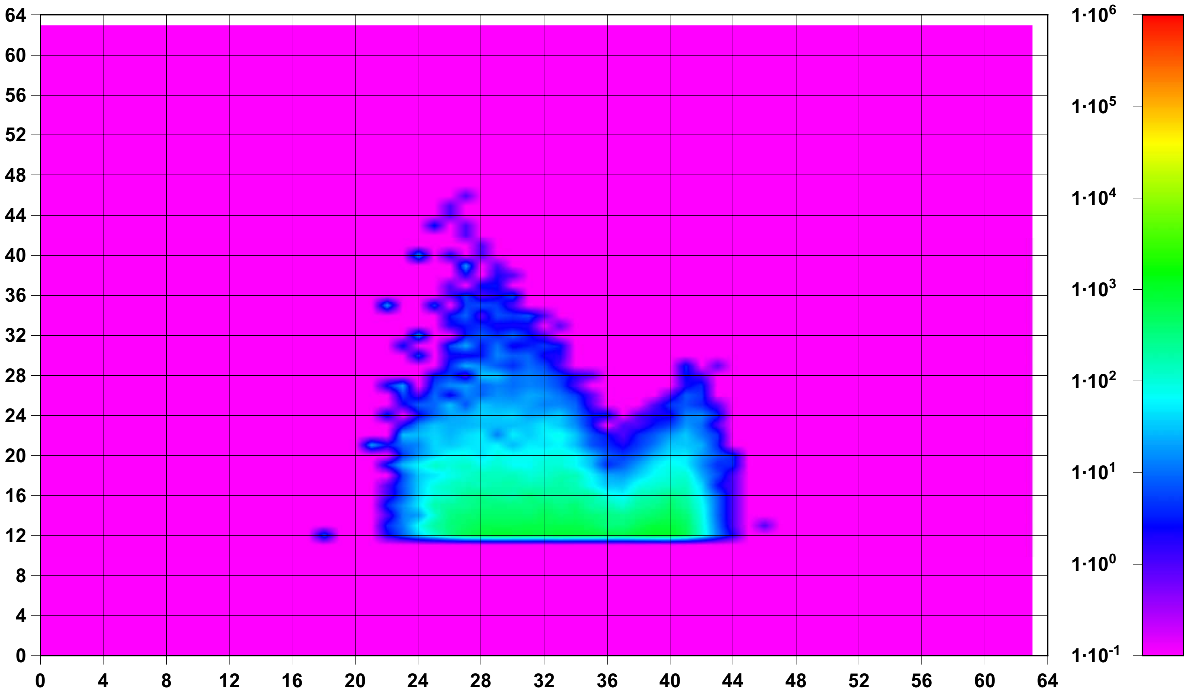


Fig. 6 : NEW WISPER Range Mean Rainflow Matrix after Omission and Reduction

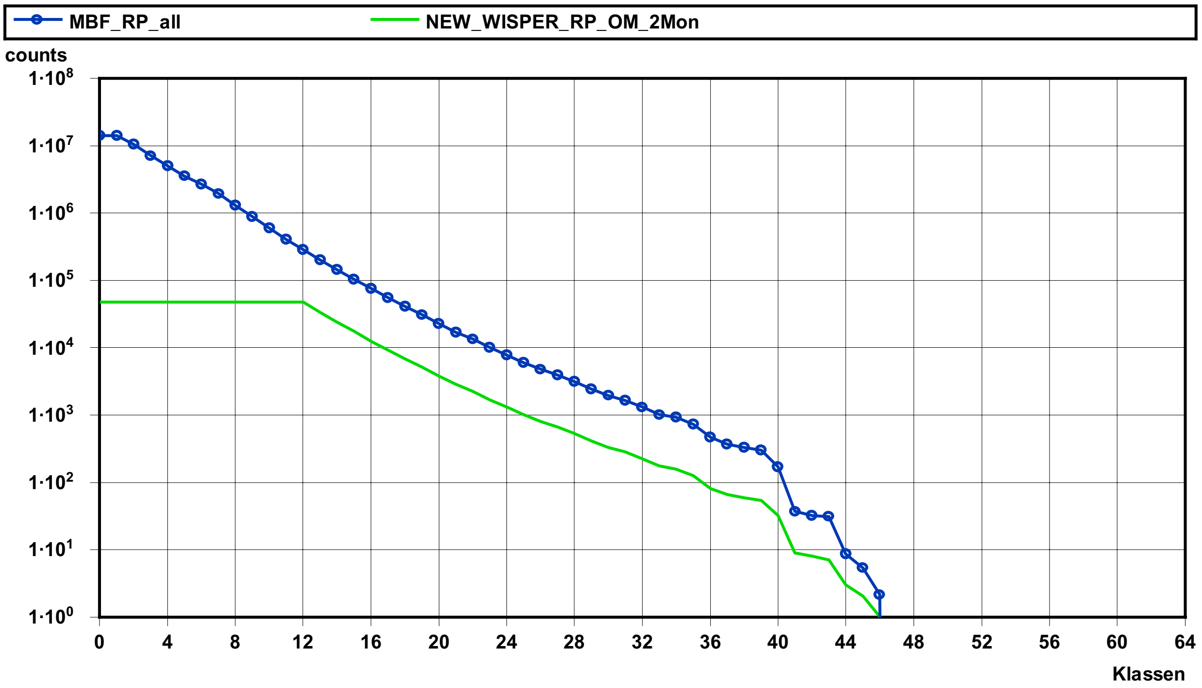


Fig. 7 : NEW WISPER Range Pair Spectrum after Omission and Reduction

4.2.8 STEP 8: Get Sequence from Rainflow matrix (DEWI)

Applying a standard rainflow equivalent routine the load cycle content of the **NEW WISPER** matrix was cast into a **NEW WISPER** sequence that looks quite different from its predecessor (compare Fig 8 and 9). As becomes clear the routine used on **NEW WISPER** does not involve a random scheme. Nevertheless, performing a Rainflow count on the **NEW WISPER** sequence will result in the identical Rainflow matrix from which it was generated - with one slight difference: After re-analyzing the NEW WISPER sequence with the rainflow counter an additional cycle is found that runs from the absolute minimum to the absolute maximum. This cycle rises from residuum treatment which was defined to treat every remaining half cycle in the residuum as a full cycle [5]. The same happened in the formation of WISPER – see Fig.9.

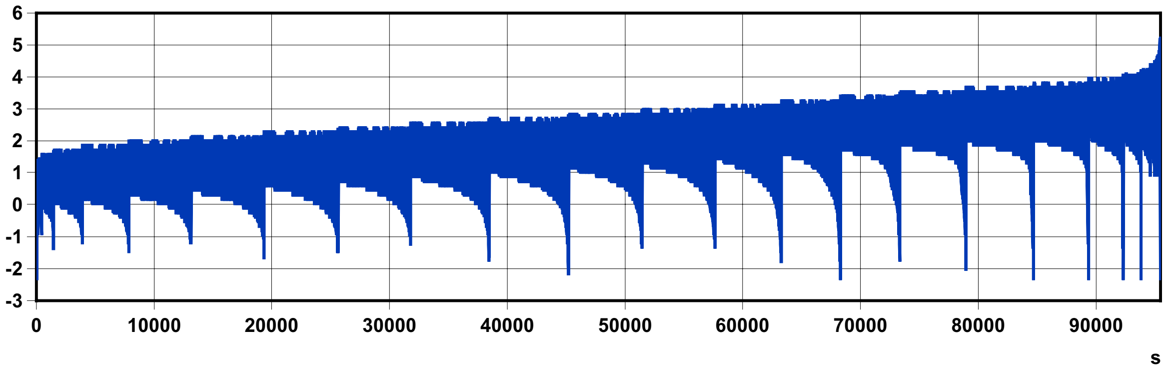


Fig. 8 : NEW WISPER Sequence Reconstructed From NEW WISPER Rainflow Matrix

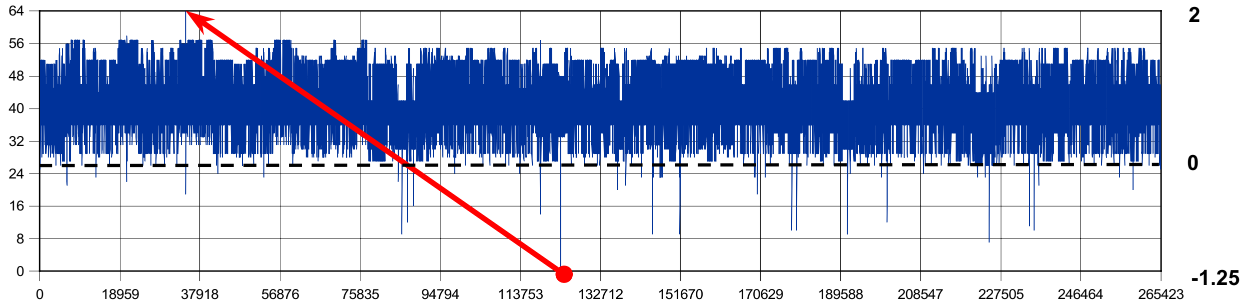


Fig. 9 : WISPER Sequence ●⟶ Extra Cycle Added When Rainflow Counting

Due to omission of small load cycles and due to reduction of the number of cycles by a factor of 6 (see step 7) the **NEW WISPER** spectrum holds a considerably smaller number of cycles than **WISPER**: 47702 vs. 132710. This difference is mainly due to the large difference in the reference rotor speed 16 rpm for **NEW WISPER** and 45 rpm for **WISPER !!**

4.2.9 Check of NEW WISPER Sequence for Rainflow Consistency (DEWI)

To check that the applied routine for time series reconstruction is working rainflow consistent the created NEW WISPER sequence has been re-analysed with the rainflow counting algorithm. The recounted rainflow matrix has 47735 load cycles – 33 more than the original NEW WISPER matrix. Again as with WISPER an additional load cycle was created through the residuum, giving a maximum range of the recounted range pair spectrum of 54 bins, some 8 bins more than the original maximum.

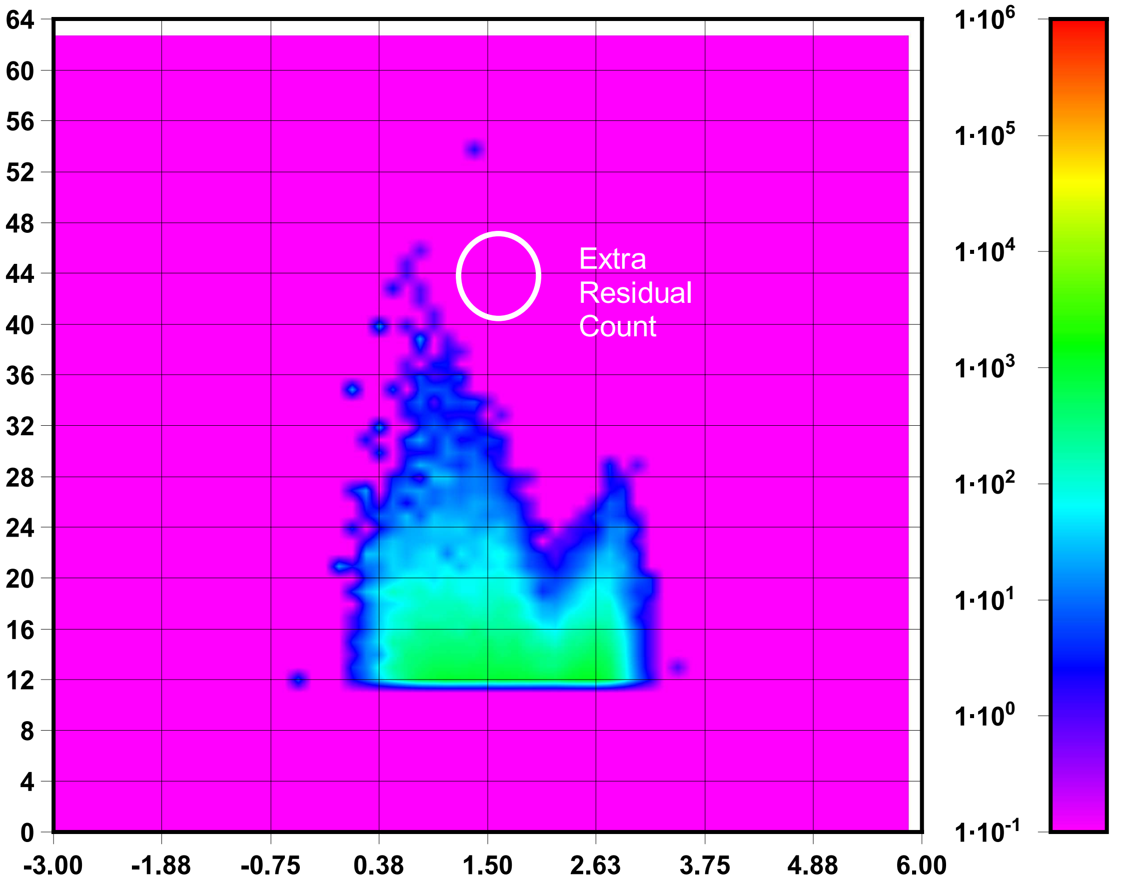


Fig. 10 : NEW WISPER Range Mean Matrix Recounted from NEW WISPER SEQ

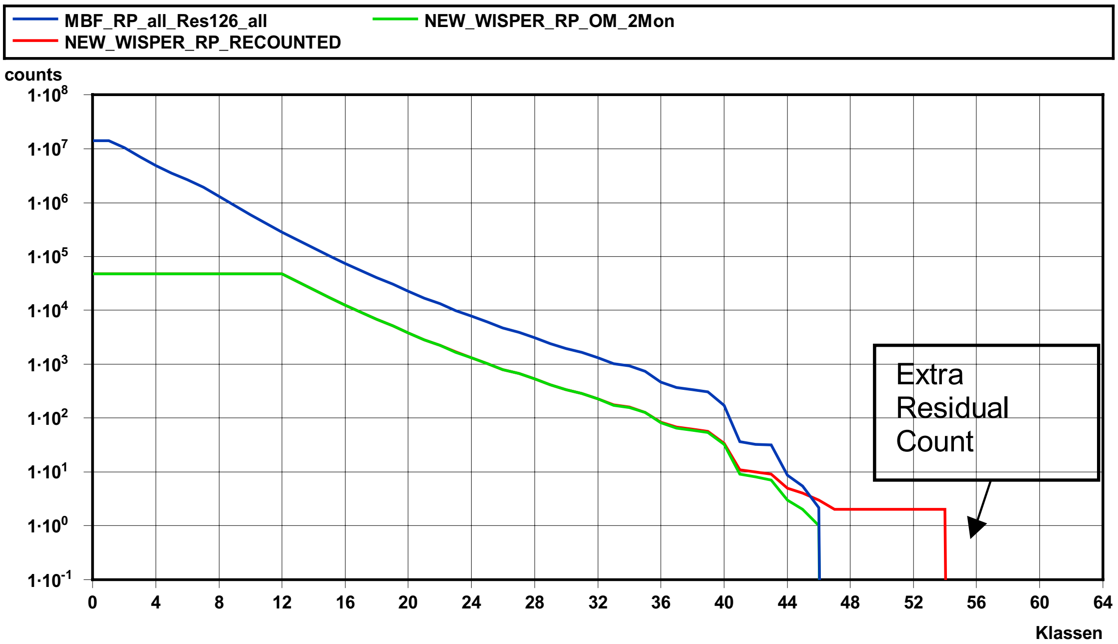


Fig. 11 : NEW WISPER Range Pair Spectrum after Omission and Reduction

5 COMPARING WISPER VS. NEW WISPER

When comparing WISPER and NEW WISPER visually (see Fig. 13) it becomes obvious that NEW WISPER has more of a “body” as compared to the isolated counts in WISPER. From experience of the authors it can be concluded that NEW WISPER is more likely what one would get to see when establishing the flatwise range mean matrix for any serial produced on a sound the basis of measured data.

It must be noted that in case of NEW WISPER for technical reasons omission has been applied to the combined rainflow matrix while for WISPER this has obviously not been done. Therefore we see some counts even underneath the omission line.

5.1 Rating WISPER / NEW WISPER Based on 1-Hz Equivalent Load Criterion

For a simple comparison of WISPER and NEW WISPER the 1-Hz equivalent load (L_{eq} , formula given in Fig.12) has been applied on the range pair spectra depicted in Fig.6. It must be noted that both load spectra have been scaled to an equal absolute strain level at the absolute maximum measured load level. Table 1 gives the results obtained for characteristic materials such as glass fiber (m=10 – 12, m = S-N curve slope in log-log diagram):

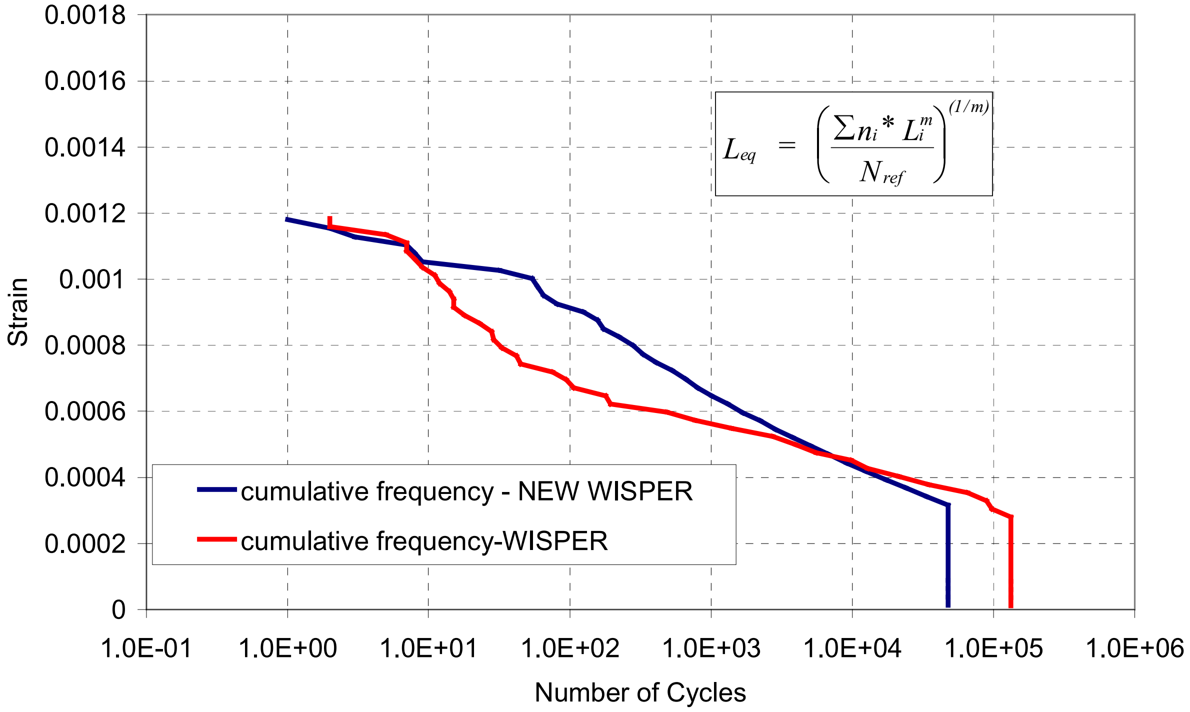
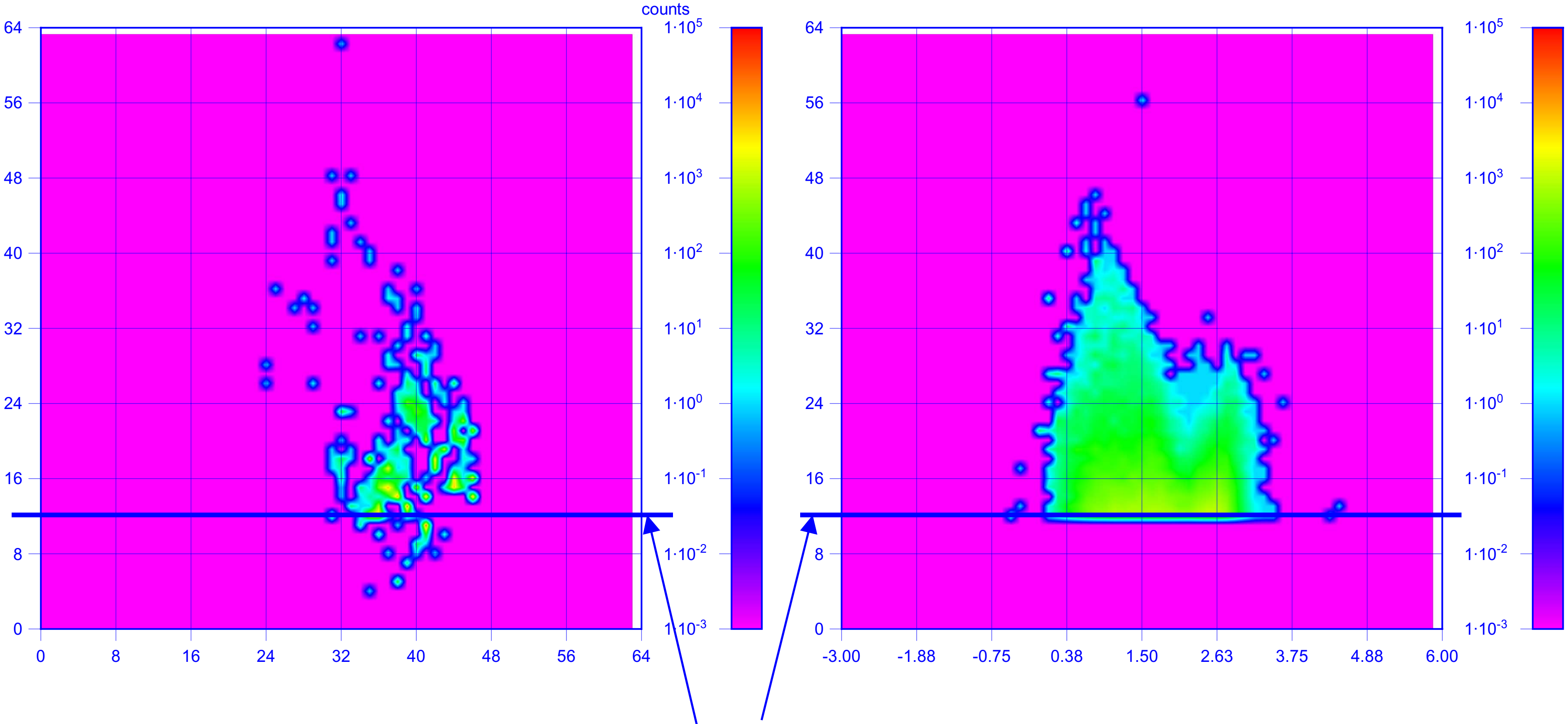


Fig. 12 : NEW WISPER / WISPER Range Pair Spectra Scaled to Equal Strain at Max. Measured Load Level

Table 3 holds the results: NEW WISPER has a 10- 12% higher equivalent load compared to WIPSER for material exponents >8. Cross referencing to the range pair spectra in Fig. 12 this result appears plausible as there is a larger cumulative number of load cycles for strain levels above 0.0004 for NEW WISPER. When evaluating the equivalent load for S-N curve slopes < 6 the picture is reversed: for m=3 (characteristic for welded steel) NEW WISPER equivalent load reduces to 81% of that of WISPER.

material exponent	3	4	6	8	10	12
equiv. No. of cycles	5256000	5256000	5256000	5256000	5256000	5256000
EQL NEW WISPER	0.000084576	0.000129923	0.000211484	0.000286545	0.000355766	0.000417516
EQL WISPER	0.000104147	0.000144157	0.000205511	0.000258818	0.000318461	0.000382702
Ratio	81.21%	90.13%	102.91%	110.71%	111.71%	109.10%

Table 3: Equivalent Load Comparison of WISPER vs. NEW WISPER



Omission Level 12 bins

Fig 13: WISPER and NEW WISPER – Visual Comparison of Range Mean Matrices

5.2 Rating WISPER / NEW WISPER Based on DLR Damage Calculations

NOTE: This evaluation has been created on a preliminary NEW WISPER load spectrum. For the final NEW WISPER load spectrum one of the wind turbines had to be reevaluated as the data base had to be enlarged considerably. Nevertheless, the resulting final NEW WISPER standard does not differ significantly from the preliminary version which was the basis for the following investigation. The authors think it would be reasonable to supply this peace of information to the reader despite the fact that the figures are in fact quantitatively incorrect but surely qualitatively good.

To investigate further DLR has carried out damage calculations employing experimental material data determined with a material that is typically applied wind turbine in rotor blades. The fatigue behavior of this material is characterized by means of several S-N curves at different R-ratios i.e. the ratio of the minimum applied strain to the maximum applied strain and static material parameters s. a. UTS (= ultimate tensile strength) and UCS (= ultimate compressive strength). Using these material data Goodman Diagrams (Fig. 14) or Constant Life Diagrams (Fig.15) of specific materials are derived. From these material data for a given load cycle range the allowable number of load cycles is found through spatial interpolation and compared to the number of load cycles found in the fatigue load spectrum using linear Palmgren-Miner's Rule.

Table 4 presents the results of these computations in terms of the WISPER/NEW WIPER ratio of the Miner sum:

Stress Level	Ratio Damage Sum	
Mpa	Goodman	CLD
100	153.04%	361.53%
200	184.32%	409.14%
300	228.37%	441.21%

Table 4 : WISPER / NEW WISPER Damage Sums Rated by DLR Damage Calculations

The computations have been performed for several stress levels and employing experimental data for a typical wind turbine in rotor blade material. The determined ratios surprisingly contradicts the assessment by the 1-Hz- L_{eq} –criterion: in any case the WISPER spectrum is creating a considerably larger damage sum! Using the Goodman diagram WISPER's miner sum is some 50% to 100% larger depending on the stress level considered. The effect becomes even more pronounced when looking at the damage ratios for CLD calculations: here the old WISPER creates 4 times as much damage as the NEW WISPER spectrum.

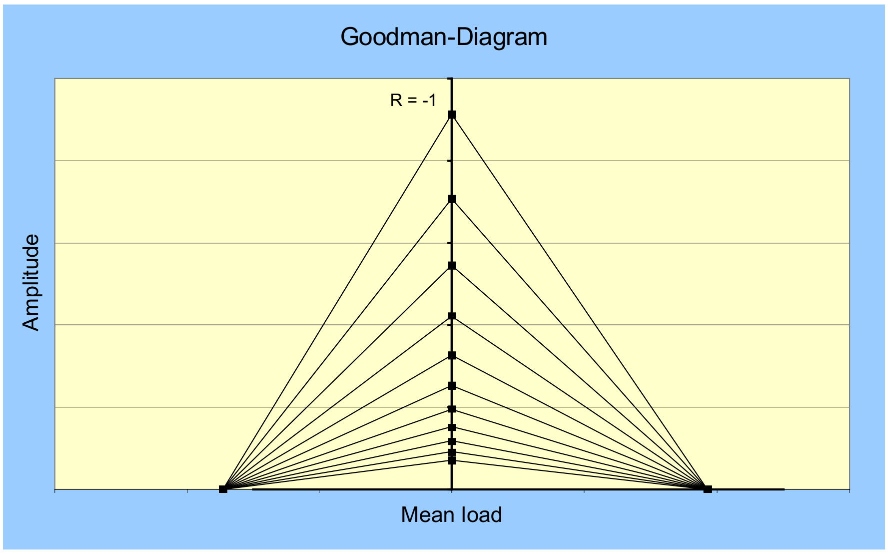


Fig. 14: Goodman Diagram

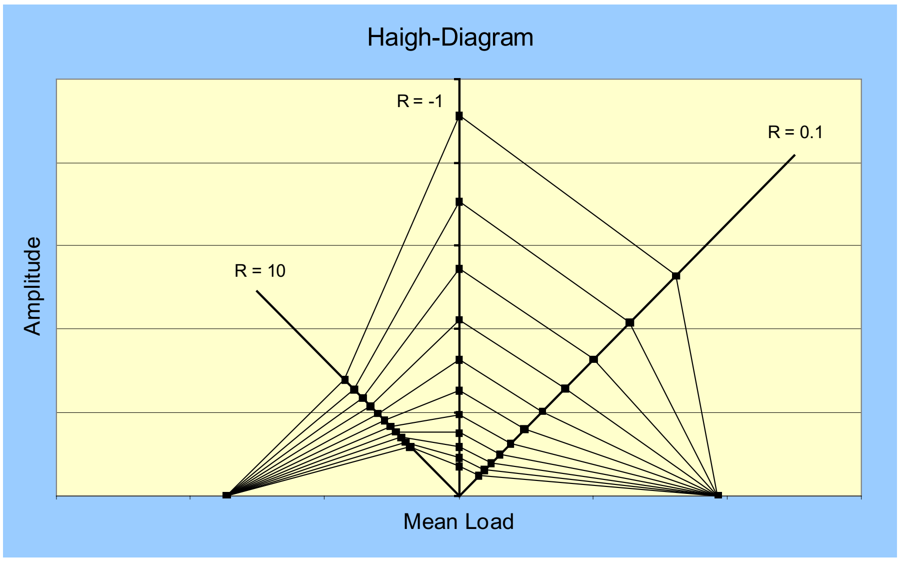


Fig. 15: Constant Life Diagram

6 CONCLUSIONS

In general the authors conclude that the major goals in establishing a NEW WISPER standard sequence have been achieved i.e. NEW WISPER reflects today's wind turbine technology and at the same time is based on a very broad data base covering more than 2600 hours of measurements. Hence NEW WISPER can be considered statistically approved. Evaluating the shapes of the spectra and the sequence distinctly different characteristics s. a. smaller cyclic content, broader spread of load cycles, more damage accumulation for large material exponents are found.

Unfortunately not all damage qualifiers applied deliver consistent results: damage calculations by DLR using more complex material descriptions and considering also the mean load level at which the individual load cycle occur deliver less conservative results for the NEW WISPER sequence. This point certainly needs further attention and clarification.

Finally, the NEW WISPER sequence is Rainflow consistent but looks somewhat unnatural. The sequence is still to be applied by the OPTIMAT BLADES project partners in actual material testing.

7 REFERENCES

[1] www.wmc.tudelft.nl/optimat_blades/

[2] ten Have, A. A.: WISPER and WISPERX: Final Definition of Two Standardised Fatigue Load Sequences For Wind Turbine Blades. Amsterdam: National Aerospace Laboratory NLR, Amsterdam, The Netherlands, 1992 (Technical Publication NLR TP 91476 U)

[3] Bulder,B.; Lekou, D.; Vionis,P.; Nijssen, Rogier P.L.; Kramkowski,T.; Söker, H.: SYNTHESIS PROCESS OF A NEW WISPER LOAD SPECTRUM. DEWI (Editor): Rev. 2 unpublished document within OPTIMAT BLADES. Wilhelmshaven, August 31, 2004.

[4] 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

[5] Kaufeld,N; Lekou, D.; Peeringa, J.; Söker, H.: OPTIMAT BLADES – NEW WISPER BENCHMARKING. doc# 10228 - OB_TG1_R019, www.wmc.tudelft.nl/optimat_blades, 2005.

ANNEX I
LIST OF DOCUMENTS PREPARED IN TG1 WP4

Final version of the document containing the procedure of the new wisper synthesis. Document title: "SYNTHESIS PROCESS OF A NEW WISPER LOAD SPECTRUM" Authors: B. Bulder - ECN, D.J. Lekou, P. Vionis - CRES, R.P.L. Nijssen - TUDelft, T. Kramkowski, H. Söker - DEWI
doc# 10225 - OB_TG1_R016

2. Final version of the document Annual_range_pair_benchmark_2nd round, including contribution and conclusions of all partners participating in the 2nd round of the round robin test. Document title: "NEW WISPER RANGE PAIR- BENCHMARKING; 2nd round" Authors: J. Peeringa - ECN, D.J. Lekou - CRES, N. Kaufeld, H. Söker - DEWI
doc# 10228 - OB_TG1_R019

3. Final version of the document Annual_range_pair_benchmark_1st round, including contribution and conclusions of all partners participating in the 1st round of the round robin test. Document title: "NEW WISPER RANGE PAIR-BENCHMARKING" Authors: J. Peeringa - ECN, D.J. Lekou - CRES, N. Kaufeld, H. Söker - DEWI
doc# 10227 - OB_TG1_R018

4. Final version of the document Rainflow_benchmark including contribution and conclusions of all partners participating in this round robin test. Document title: "RAINFLOW - EQL - BENCHMARKING" Authors: B. Bulder - ECN, D. Lekou, F. Mouzakis - CRES, H. Söker - DEWI.
doc# 10226 - OB_TG1_R017

5. DEWEK-Paper on NEW WISPER published December 2004
Document Title:NEW WISPER - Creating a New Load Sequence From Modern Wind Turbine Data, Authors:Christoph Kensche, Olaf Krause - DLR, Holger Söker, Norbert Kaufeld - DEWI
doc# 10229 - OB_TG1_P004

6.DEWI-Magazin-Article on NEW WISPER published August 2004 as announced on Patras Meeting:
Document title:NEW WISPER: A New Edition of The Classic Fatigue Load Sequence WISPER for Variable Amplitude Testing on Materials Used in Wind Energy Industries, Author :Holger Söker - DEWI
doc# 10230 - OB_TG1_P005

ANNEX II
DATA BASE DESRIPTIONS

DESCRIPTION OF THE DATA BASES USED IN THE ESTABLISHMENT OF A NEW WISPER LOAD SPECTRUM

Turbine 1.5MW (Name of manufacturer and type of turbine withheld)

General Characteristics

TURBINE MAIN SPECIFICATIONS	
Rotor diameter	70 m
Rated Power Output	1500 kW
Power Control	Pitch Control / variable
Rotor speed (range / 1st 2nd speed)	11 – 20
Number of Blades	3
Rotor position	Upwind (luv)
Hub height	85 m
Prototype / Serial WEC	Prototype
Cut-in Wind Speed	3 m/s
Rated Wind Speed	12 m/s
Cut-out Wind Speed	22 m/s

Description of The Site

- The turbine is on a site with flat rural terrain. At times neighbouring operating turbines and other industrial obstacles influence the measured wind turbine or ist mast .
- With omission these influencing sectors the collected data is from sector 15°-45° and 210°-300° as seen in the table 1.1.4.4.
- The mean turbulence of the sector is 8.8%
- The distance between meteorological-mast and turbine is 2.5 rotor diameter.

Instrumentation

Load Quantity	Instrumentation	Remarks
Blade Root Flap Bending	Full Strain Gauge Bridge	Distance to blade flange: 700mm
Blade Root Lead-Lag Bending	Full Strain Gauge Bridge	Distance to blade flange: 700mm

Table of load quantities measured and remarks.

Quantity	Instrumentation	Remarks
Wind Speed	Anemometer	Measured at Hub Height and 50m on Met.-Mast, and on Nacelle
Wind Direction	Wind Vane	Wind Direction at Hub Height
Electrical Power	Power Transducer	Turbine Cabinet

Table of meteorological / operational quantities measured and remarks.

Description of Amount and Quality of Available Data

Following table presents the normal power production capture matrix from the measurement sector. The start and stop data sets were not classified into sectors.

V(m/s) I(%)	0 3.5	3.5 4.5	4.5 5.5	5.5 6.5	6.5 7.5	7.5 8.5	8.5 9.5	9.5 10.5	10.5 11.5	11.5 12.5	12.5 13.5	13.5 14.5	14.5 15.5	15.5 16.5	16.5 17.5	17.5 18.5	18.5 19.5	19.5 20.5	20.5 21.5	>21.5 V out
0- <3			**2**	**6**	**3**	**3**	**5**	**3**												
3- 5			**6**	**4**	**15**	**4**	**7**	**1**												
5- 7		**1**	**4**	**9**	**23**	**11**	**8**	**1**												
7- 9	**1**	**2**	**9**	**17**	**11**	**7**	**5**	**6**	**6**	**2**		**4**								
9- 11	**3**		**4**	**5**	**3**	**6**	**19**	**31**	**21**	**16**	**11**	**7**	**4**	**1**	**1**	**2**	**2**			
11- 13		**2**	**7**	**2**	**1**	**6**	**21**	**25**	**18**	**21**	**20**	**20**	**18**	**6**	**6**		**4**	**1**		**1**
13- 15		**3**	**1**	**1**			**4**	**8**	**5**	**7**	**5**	**11**	**5**	**1**	**3**	**4**	**3**	**2**		
15- 17		**1**						**3**	**1**	**1**	**2**	**1**	**1**	**1**	**3**	**1**				
17- 19		**1**					**1**													
19- 21									**1**											
21- 23																				
23- 25																				
25- 27																				
27- 29																				
>29	**1**																			
Starts	6	7	1			1				2	1					1				
Stops	1																			
	12	17	34	44	56	38	70	78	52	49	39	43	28	9	13	8	9	3	0	1

Datasets : **603**

Capture Matrix of normal operation (sector 15°-45° and 210°-300°)

Three emergency stop transients were recorded between 13 and 15 m/s.

Therefore, the resulting capture matrix of data used in the analysis of turbulence bin of 11-13% width is shown in the following table

V(m/s) I(%)	0 3.5	3.5 4.5	4.5 5.5	5.5 6.5	6.5 7.5	7.5 8.5	8.5 9.5	9.5 10.5	10.5 11.5	11.5 12.5	12.5 13.5	13.5 14.5	14.5 15.5	15.5 16.5	16.5 17.5	17.5 18.5	18.5 19.5	19.5 20.5	20.5 21.5	>21.5 V out
0- <3																				
3- 5																				
5- 7																				
7- 9																				
9- 11	**3**		**4**	**5**	**3**	**6**	**19**	**31**	**21**	**16**	**11**	**7**	**4**	**1**	**1**	**2**	**2**			
11- 13		**2**	**7**	**2**	**1**	**6**	**21**	**25**	**18**	**21**	**20**	**20**	**18**	**6**	**6**		**4**	**1**	***1***	***4***
13- 15		**3**	**1**	**1**			**4**	**8**	**5**	**7**	**5**	**11**	**5**	**1**	**3**	**4**	**3**	**2**	***2***	
15- 17																				
17- 19																				
19- 21																				
21- 23																				
23- 25																				
25- 27																				
27- 29																				
>29																				
	3	5	12	8	4	12	44	64	44	44	36	38	27	8	10	6	9	3	3	4

Datasets :	**384**
mean Turbulence:	**11.63**

Missing data for wind bins 21 and 22 were substituted by data from wind bin 20 shown in ***blue italics***.

Used transient manoeuvres

The capture matrix (actual measured events/wind speed) for normal transient events

Normal start-up and shut-down events		
Event	$V_{in} < V < V_r - 2$ m/s	$V > V_r$
Start-up	8	1
Normal shut-down	1	-

Capture matrix for other than normal transient events

Other transient events	
Event	**Number of events**
Emergency shut-down	3

Normalisation of flatwise bending moments

Normalised maximum instantaneous flatwise loads: 4
Normalised minimum instantaneous flatwise loads: -2

Analysis conducted using normalised flatwise loads: -3, +6

Annual cumulated Rainflow load spectra

Used Weibull with A=9.59 and C=2.0
Rainflow parameters: Hysteresis = 1.1x bin width = 0.15469, counting of residuals as full cycles

Normalisation of cyclic content (rotational speed)

For the normalisation the reference number of rotor revolutions was defined as 16rpm constant rotor speed as agreed in the group.
Normalization Factor Used: 1,103868317

Add low cyclic loads for each turbine and transient loads

Load Cycles from Annual Wind Speed Time History of 10min-Averages According to RISØ-Method:

Based on the annual wind speed time series supplied by DEWI a load time series of Min / Max loads of length 101684 was created and Rainflow-counted

Load Cycles from Starts and Stops / Emergency Stops / Other Transients:

Number of starts at V_{in}: 404
Number of stops at V_{in}: 404
Number of starts at V_{out}: 17
Number of stops at V_{out}: 17
Emergency stops: 40

Turbine 2.5MW (Name of manufacturer and type of turbine withheld)

General Characteristics

TURBINE MAIN SPECIFICATIONS	
Rotor diameter	80 m
Rated Power Output	2500 kW
Power Control	Pitch Control / variable
Rotor speed (range / 1st 2nd speed)	10.2 – 19.2
Number of Blades	3
Rotor position	Upwind (luv)
Hub height	80 m
Prototype / Serial WEC	Prototype
Cut-in Wind Speed	3 m/s
Rated Wind Speed	15 m/s
Cut-out Wind Speed	25 m/s

Description of The Site

- The turbine is on a site with flat rural terrain. At times neighbouring operating turbines and other industrial obstacles influence the measured wind turbine or its mast .
- With omission these influencing sectors the collected data is from sector 182° - 310° as seen in the capture matrix below
- The mean turbulence of the sector is 9.8%
- The distance between meteorological-mast and turbine is 2.5 rotor diameter.

Instrumentation

Load Quantity	Instrumentation	Remarks
Blade Root Flap Bending	Full Strain Gauge Bridge	Distance to blade flange: 600mm
Blade Root Lead-Lag Bending	Full Strain Gauge Bridge	Distance to blade flange: 600mm

Table of load quantities measured and remarks.

Quantity	Instrumentation	Remarks
Wind Speed	Anemometer	Measured at Hub Height, Met.-Mast
Wind Speed	Anemometer	Measured on Nacelle
Wind Direction	Wind Vane	Wind Direction at Hub Height
Electrical Power	Power Transducer	

Table of meteorological / operatiuonal quantities measured and remarks.

Description of Amount and Quality of Available Data

Following table presents the normal power production capture matrix from the measurement sector. The start and stop data sets were not classified into sectors.

Wind speed bin size (x-axis): **1 m/s**
Turbulence bin size (y-axis) : **2%**

V(m/s) I(%)	0 3.5	3.5 4.5	4.5 5.5	5.5 6.5	6.5 7.5	7.5 8.5	8.5 9.5	9.5 10.5	10.5 11.5	11.5 12.5	12.5 13.5	13.5 14.5	14.5 15.5	15.5 16.5	16.5 17.5	17.5 18.5	18.5 19.5	19.5 20.5	20.5 21.5	>21.5 V out
0- <3		**2**	**23**	**26**	**27**	**8**														
3- 5		**7**	**18**	**40**	**32**	**27**	**2**	**2**	**2**											
5- 7		**4**	**15**	**32**	**27**	**12**	**9**	**9**	**5**											
7- 9		**12**	**29**	**17**	**36**	**32**	**23**	**25**	**24**	**8**	**2**	**3**	**2**		**1**				**1**	
9- 11		**7**	**13**	**29**	**33**	**29**	**20**	**22**	**14**	**6**	**5**	**5**	**5**	**4**	**5**	**9**	**10**	**6**	**1**	
11- 13		**23**	**23**	**37**	**30**	**27**	**27**	**35**	**34**	**4**	**11**	**12**	**4**	**11**	**19**	**13**	**14**	**11**	**2**	
13- 15		**15**	**19**	**12**	**17**	**16**	**12**	**23**	**10**	**7**	**5**									
15- 17		**4**	**5**	**2**	**9**	**5**	**4**	**5**		**2**	**1**									
17- 19			**1**		**1**	**2**	**1**			**1**										
19- 21		**1**		**1**	**1**			**1**	**2**											
21- 23		**1**																		
23- 25					**2**															
25- 27																				
27- 29		**1**																		
>29		**1**																		
Starts	2	2	1	2	3	3	2	5	1	2	3	26								
Stops							1	1												
	2	80	147	198	218	161	101	128	92	30	27	46	11	15	25	22	24	17	4	0

Datasets : **1348**

Shut down transients at 9 and 19 m/s discarded!
Two manual shut down transients were recorded at 14 and 19 m/s.

V(m/s) I(%)	0 3,5	3,5 4,5	4,5 5,5	5,5 6,5	6,5 7,5	7,5 8,5	8,5 9,5	9,5 10,5	10,5 11,5	11,5 12,5	12,5 13,5	13,5 14,5	14,5 15,5	15,5 16,5	16,5 17,5	17,5 18,5	18,5 19,5	19,5 20,5	20,5 21,5	>21.5 V out
0-<3																				
3-5																				
5-7																				
7-9	**7**	**7**	**13**	**9**	**25**	**22**	**14**	**19**	**20**	**6**	**2**	**2**	**2**		**1**				**1**	**4**
9-11	**5**	**5**	**10**	**17**	**16**	**24**	**18**	**21**	**14**	**6**	**5**	**5**	**5**	**4**	**5**	**9**	**10**	**6**	**1**	**4**
11-13	**18**	**18**	**23**	**22**	**19**	**17**	**14**	**19**	**24**	**4**	**11**	**12**	**4**	**11**	**19**	**13**	**14**	**11**	**2**	**8**
13-15																				
15-17																				
17-19																				
19-21																				
21-23																				
23-25																				
25-27																				
27-29																				
>29																				
	30	30	46	48	60	63	46	59	58	16	18	19	11	15	25	22	24	17	4	16
start			7								4									
estop													1				1			

Datasets :	**627**
mean Turbulence:	**10,41**

Missing data for wind bin 3 were substituted by data from wind bin 4 shown in ***blue italics***.
Missing data for wind bins 22 to 25 were substituted by data from wind bin 21 shown in ***blue italics***.

Used transient manoeuvres

The capture matrix (actual measured events/wind speed) for normal transient events

Normal start-up and shut-down events		
Event	$V_{in} < V < V_r - 2$ m/s	$V > V_r$
Start-up	11	-
Normal shut-down	see other transient-	see other transient

Capture matrix for other than normal transient events

Other transient events	
Event	**Number of events**
Emergency shut-down/ Manual shut-down	2

Normalisation of flatwise bending moments

Normalised maximum instantaneous flatwise loads:
Normalised minimum instantaneous flatwise loads: -2

Analysis conducted using normalised flatwise loads: -3, +6

Annual cumulated Rainflow load spectra

Used Weibull with A=9.59 and C=2.0
Rainflow parameters: Hysteresis = 1.1x bin width = 0.15469, counting of residuals as full cycles

Normalisation of cyclic content (rotational speed)

For the normalisation the reference number of rotor revolutions was defined as 16rpm constant rotor speed as agreed in the group.
Normalization Factor Used: 1,164135716

Add low cyclic loads for each turbine and transient loads

Load Cycles from Annual Wind Speed Time History of 10min-Averages According to RISØ-Method:

Based on the annual wind speed time series supplied by DEWI a load time series of Min / Max loads of length 101710 was created and Rainflow-counted

Load Cycles from Starts and Stops / Emergency Stops / Other Transients:

Number of starts at V_{in}: 404
Number of stops at V_{in}: 404
Number of starts at V_{out}: 12
Number of stops at V_{out}: 12
Emergency stops: 40

Turbine 1.25 MW (Name of manufacturer and type of turbine withheld)

General Characteristics

TURBINE MAIN SPECIFICATIONS	
Rotor diameter	64 m
Rated Power Output	1250 kW
Power Control	Pitch Control / 2 fixed speeds
Rotor speed (range / 1st 2nd speed)	13.8 – 20.7
Number of Blades	3
Rotor position	Upwind (luv)
Hub height	65 m
Prototype / Serial WEC	Prototype
Cut-in Wind Speed	3 m/s
Rated Wind Speed	12 m/s
Cut-out Wind Speed	25 m/s

Description of The Site

- The turbine is on a site with flat rural terrain. At times neighbouring operating turbines influence the measured wind turbine or mast .
- With omission these influencing sectors the collected data is from sector 240°-60° as seen in the table 1.1.4.4.
- The mean turbulence of the sector is 7.9%
- The distance between meteorological-mast and turbine is 2.5 rotor diameter.

Instrumentation

Load Quantity	Instrumentation	Remarks
Blade Root Flap Bending	Full Strain Gauge Bridge	Distance to blade flange: 700mm
Blade Root Lead-Lag Bending	Full Strain Gauge Bridge	Distance to blade flange: 700mm

Table of load quantities measured and remarks.

Quantity	Instrumentation	Remarks
Wind Speed	Anemometer	Measured at Hub Height on Met.-Mast, and on Nacelle
Wind Direction	Wind Vane	Wind Direction at Hub Height
Electrical Power	Power Transducer	Turbine Cabinet

Table of meteorological / operational quantities measured and remarks.

Description of Amount and Quality of Available Data

Following table presents the normal power production capture matrix from the measurement sector. The start and stop data sets were not classified into sectors.

V(m/s) I(%)	0 3.5	3.5 4.5	4.5 5.5	5.5 6.5	6.5 7.5	7.5 8.5	8.5 9.5	9.5 10.5	10.5 11.5	11.5 12.5	12.5 13.5	13.5 14.5	14.5 15.5	15.5 16.5	16.5 17.5	17.5 18.5	18.5 19.5	19.5 20.5	20.5 21.5	>21.5 V out
0- <3			4	4	5	1														
3- 5		24	21	22	30	13	8													
5- 7	1	46	94	84	112	123	73	54	43	12	9	4								
7- 9	3	29	89	116	189	248	407	310	217	132	50	19	12	2	1					
9- 11		2	18	21	51	100	143	113	107	65	21	20	4	3						
11- 13		1	1		1		1	3	3	3				1						
13- 15																				
15- 17																				
17- 19																				
19- 21																				
21- 23																				
23- 25																				
25- 27																				
27- 29																				
>29																				
	4	102	227	247	388	485	632	480	370	212	80	43	16	6	1	0	0	0	0	0

Datasets :	**3293**
mean Turbulence:	**7.86**

Capture Matrix of normal operation (sector 15°-45° and 210°-300°)

Three emergency stop transients were recorded between 13 and 15 m/s.

Therefore, the resulting capture matrix of data used in the analysis of turbulence bin of 5-11% width is shown in the following table

V(m/s) I(%)	0 3.5	3.5 4.5	4.5 5.5	5.5 6.5	6.5 7.5	7.5 8.5	8.5 9.5	9.5 10.5	10.5 11.5	11.5 12.5	12.5 13.5	13.5 14.5	14.5 15.5	15.5 16.5	16.5 17.5	17.5 18.5	18.5 19.5	19.5 20.5	20.5 21.5	>21.5 V out
0- <3																				
3- 5																				
5- 7	1	46	94	84	112	123	73	54	43	12	9	4								
7- 9	3	29	89	116	189	248	407	310	217	132	50	19	12	2+1	1 + 2	1 + 2	1 + 2	1 + 2	1 + 2	12
9- 11		2	18	21	51	100	143	113	107	65	21	20	4	3	3	3	3	3	3	12
11- 13																				
13- 15																				
15- 17																				
17- 19																				
19- 21																				
21- 23																				
23- 25																				
25- 27																				
27- 29																				
>29																				
	4	77	201	221	352	471	623	477	367	209	80	43	16	6	6	6	6	6	6	24

Datasets :	**3201**
mean Turbulence:	**7.98**

Missing data were substituted by data from adjacent wind / turbulence bins as shown in ***blue italics***.

Used transient manoeuvres

The capture matrix (actual measured events/wind speed) for normal transient events between two generator modes:

V(m/s)	0	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	>21.5
I(%)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5	V out
UP				**7**	**10**	**3**	**1**	**1**												
DOWN		**3**	**9**	**8**	**2**															
	0	3	9	15	12	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0

Datasets : 44

The capture matrix (actual measured events/wind speed) for normal start–up and shut-down events

Normal start-up and shut-down events		
Event	$V_{in} < V < V_r - 2$ m/s	$V > V_r$
Start-up	8	1
Normal shut-down	1	-

Capture matrix for other than normal transient events

Other transient events	
Event	**Number of events**
Emergency shut-down	3

Normalisation of flatwise bending moments

Normalised maximum instantaneous flatwise loads: 4
Normalised minimum instantaneous flatwise loads: -2

Analysis conducted using normalised flatwise loads: -3, +6

Annual cumulated Rainflow load spectra

Used Weibull with A=9.59 and C=2.0
Rainflow parameters: Hysteresis = 1.1x bin width = 0.15469, counting of residuals as full cycles

Normalisation of cyclic content (rotational speed)

For the normalisation the reference number of rotor revolutions was defined as 16rpm constant rotor speed as agreed in the group.
Normalization Factor Used: 0,9357412

Add low cyclic loads for each turbine and transient loads

Load Cycles from Annual Wind Speed Time History of 10min-Averages According to RISØ-Method:

Based on the annual wind speed time series supplied by DEWI a load time series of Min / Max loads of length 101710 was created and Rainflow-counted

Load Cycles from Starts and Stops / Emergency Stops / Other Transients:

Number of starts at V_{in}: 404
Number of stops at V_{in}: 404
Number of starts at V_{out}: 12
Number of stops at V_{out}: 12
Emergency stops: 40

Transitions from generator stage II up to stage I (larger stage): 726
Transitions from generator stage I down to stage II (larger stage): 440

Turbine 1.3 MW (Name of manufacturer and type of turbine withheld)

General Characterictics

TURBINE MAIN SPECIFICATIONS	
Rotor diameter	70m
Rated Power Output	1300 kW
Power Control	Pitch Control / variable
Rotor speed (range / 1st 2nd speed)	11.6 – 21.6
Number of Blades	3
Rotor position	Upwind (luv)
Hub height	60 m
Prototype / Serial WEC	Prototype
Cut-in Wind Speed	3 m/s
Rated Wind Speed	11 m/s
Cut-out Wind Speed	18 m/s

Site description

- The turbine is in a wind park in a very complex terrain of hills and woodland.
- Wake inflow conditions caused by smaller and lower neighbouring turbines reduce measurement sector to 332° - 56°.
- The mean turbulence of the sector is 7.7%
- The distance between meteorological-mast and turbine is 2.64 rotor diameter.

Instrumentation

Load Quantity	Instrumentation	Remarks
Blade Root Flap Bending	Full Strain Gauge Bridge	Distance to blade flange: 600mm
Blade Root Lead-Lag Bending	Full Strain Gauge Bridge	Distance to blade flange: 600mm

Table of load quantities measured and remarks.

Quantity	Instrumentation	Remarks
Wind Speed	Anemometer	Measured at Hub Height, Met.-Mast
Wind Speed	Anemometer	Measured on Nacelle
Wind Direction	Wind Vane	Wind Direction at Hub Height
Electrical Power	Power Transducer	Cabinet

Table of meteorological / operatiuonal quantities measured and remarks.

Description of Amount and Quality of Available Data

Following table presents the normal power production capture matrix from the measurement sector. The start and stop data sets were not classified into sectors.

Wind speed bin size (x-axis): **1 m/s**
Turbulence bin size (y-axis) : **2%**

V(m/s) I(%)	0 3.5	3.5 4.5	4.5 5.5	5.5 6.5	6.5 7.5	7.5 8.5	8.5 9.5	9.5 10.5	10.5 11.5	11.5 12.5	12.5 13.5	13.5 14.5	14.5 15.5	15.5 16.5	16.5 17.5	17.5 18.5	18.5 19.5	19.5 20.5	20.5 21.5	>21.5 V out
0- <3		**2**	**2**	**2**																
3- 5		**6**	**19**	**12**	**4**	**5**				**1**		**2**								
5- 7		**12**	**31**	**22**	**14**	**12**	**9**	**17**	**8**	**9**	**16**	**3**	**11**	**3**						
7- 9		**10**	**20**	**26**	**17**	**17**	**21**	**19**	**14**	**27**	**38**	**9**	**9**	**1**	**3**	**1**				
9- 11		**5**	**12**	**10**	**17**	**28**	**27**	**34**	**20**	**27**	**29**	**16**	**4**	**2**	**3**	**2**				
11- 13	**1**	**2**	**4**	**6**	**12**	**36**	**18**	**32**	**38**	**36**	**33**	**24**	**6**	**5**	**2**					
13- 15			**3**	**4**	**10**	**21**	**25**	**30**	**44**	**24**	**9**	**15**	**4**	**1**	**2**	**1**				
15- 17			**2**	**7**	**5**	**15**	**12**	**18**	**21**	**21**	**13**	**10**	**3**	**7**						
17- 19			**1**		**1**	**9**	**8**	**7**	**6**	**7**	**7**	**6**	**3**		**1**					
19- 21				**1**		**3**	**1**	**3**	**2**		**1**									
21- 23						**2**														
23- 25																				
25- 27																				
27- 29																				
>29																				
Start/Stop		12		7							1	1								
	1	49	94	97	80	148	121	160	153	152	147	86	40	19	11	4	0	0	0	0

Datasets : **1362**

Two emergency stop transients were recorded at 8 and 13 m/s.

Therefore, the resulting capture matrix of data used in the analysis of turbulence bin of 11-13% width is shown in the following table

V(m/s) I(%)	0 3.5	3.5 4.5	4.5 5.5	5.5 6.5	6.5 7.5	7.5 8.5	8.5 9.5	9.5 10.5	10.5 11.5	11.5 12.5	12.5 13.5	13.5 14.5	14.5 15.5	15.5 16.5	16.5 17.5	17.5 18.5	18.5 19.5	19.5 20.5	20.5 21.5	>21.5 V out
0- <3																				
3- 5																				
5- 7																				
7- 9		**10**	**20**	**26**	**17**	**17**	**21**	**19**	**14**	**27**	**37**	**9**	**9**	**1**	**3**	**1**	***1***	***1***	***1***	***4***
9- 11		**5**	**12**	**10**	**17**	**28**	**27**	**34**	**20**	**27**	**29**	**16**	**4**	**2**	**3**	**2**	***2***	***2***	***2***	***8***
11- 13	**1**	**2**	**4**	**6**	**12**	**36**	**18**	**32**	**38**	**36**	**33**	**24**	**6**	**5**	**2**					
13- 15			**3**	**4**	**10**	**21**	**24**	**30**	**44**	**24**	**9**	**15**	**4**	**1**	**2**	**1**	***1***	***1***	***1***	***4***
15- 17																				
17- 19																				
19- 21																				
21- 23																				
>29																				
	1	17	39	46	56	102	90	115	116	114	108	64	23	9	10	4	4	4	4	16
start						1														
stop					1															
estop	2		1								1									

Datasets : **942**

mean Turbulence: **10.88**

Missing data for wind bins above 19 were substituted by data in wind bin 18 shown in ***blue italics***.

Used transient manoeuvres

The capture matrix (actual measured events/wind speed) for normal transient events

Normal start-up and shut-down events		
Event	$V_{in} < V < V_r - 2$ m/s	$V > V_r$
Start-up	1	-
Normal shut-down	1	-

Capture matrix for other than normal transient events

Other transient events	
Event	**Number of events**
Emergency shut-down	4

Normalisation of flatwise bending moments

Normalised maximum instantaneous flatwise loads: 4
Normalised minimum instantaneous flatwise loads: -2

Analysis conducted using normalised flatwise loads: -3, +6

Annual cumulated Rainflow load spectra

Used Weibull with A=9.59 and C=2.0
Rainflow parameters: Hysteresis = 1.1x bin width = 0.15469, counting of residuals as full cycles

Normalisation of cyclic content (rotational speed)

For the normalisation the reference number of rotor revolutions was defined as 16rpm constant rotor speed as agreed in the group.
Normalization Factor Used: 1,103868317

Add low cyclic loads for each turbine and transient loads

Load Cycles from Annual Wind Speed Time History of 10min-Averages According to RISØ-Method:

Based on the annual wind speed time series supplied by DEWI a load time series of Min / Max loads of length 99454 was created and Rainflow-counted

Load Cycles from Starts and Stops / Emergency Stops / Other Transients:

Number of starts at V_{in}: 404
Number of stops at V_{in}: 404
Number of starts at V_{out}: 110
Number of stops at V_{out}: 110
Emergency stops: 40

Turbine 750 kW (Name of manufacturer and type of turbine withheld)

General Characteristics

TURBINE MAIN SPECIFICATIONS	
Rated Power Output	750 kW (Direct Drive)
Cut-in Wind Speed	3 m/s
Rated Wind Speed	13 m/s
Cut-out Wind Speed	20 m/s
Control Concept	Full span pitch to vane
Number of Blades	3

Description of The Site

Surroundings are flat farm land, a dike of 6.6 m height is positioned at 300 m to the east and 6 Bonus wind turbines are positioned to the south-east side, the closest wind turbine is almost 250 m, appr. 4.7 D, away.

Two meteorological masts are available, met-mast 1, ~1.8*D West of the turbine and met-mast 2, ~2.2*D south-east of the turbine.

Instrumentation

The relevant instrumentation is given in the following table:

Table of load quantities measured and remarks.

Load Quantity	Instrumentation	Remarks
blade root moments	strain gages	measured in cylindrical part of pitching blade, at 3.907 m from rotor centre on three blades.
Rotor RPM	From turbine controller	
Electric power	ECN power transducer	

Table of meteorological / operational quantities measured

Quantity	Instrumentation	Remarks
windspeed hub-height	Miery type 018 cup anemometer	mast 1
windspeed hub-height	Gill sonic anemometer	mast 2
windspeed hub-height	Miery type 018 cup anemometer	mast 2

Description of Amount and Quality of Available Data

The measurements have been taken on a prototype turbine during a nine month period. In this period modifications in the turbine and controller have been made and for this reason the measurement system has not been operational for the complete period.

A total number of 492 production load cases are available as ten minute time series, the majority of which include measurements of all three blades.

In the measured blade root signals, zero drift has been observed, and the presented data has been corrected for this phenomenon.

Checks of measured idle captures showed no significant change in the gain of the signal.

The available time series are summarised in the following capture matrix. The coloured cells are used in the final synthesis process.

capture matrix for normal power production

turbulence int. % (bin middle)	Windspeed (m/s) (bin middle)															
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Total
2		1	2	8	2	1										14
4		8	11	19	3	8	4	4	1	1	1					60
6		5	11	17	10	21	19	16	11	7	8	3	2	1	1	132
8		3	7	9	13	10	8	11	8	12	10	4	3	4	1	103
10		3	2	8	6	4	7	5	4	4	6	2				51
12	1	3	7	5	11	10	3	3	2	4	5	4				58
14	1	2	9	5	3	3	6	3	1	2		1				36
16		3	6		1	2	1	1	2							16
18	3	4	1	1	2	1	1	2								15
20	1	1	1	1		1	1									6
22					1											1
	6	33	57	73	52	61	50	45	29	30	30	14	5	5	2	492

Captures of transient manoeuvres

A total number of 14 starts and/or stops are available as timeseries. See the capture matrix below. In the final synthesis process the timeseries in the coloured cells are used.

capture matrix for start and stops

turbulence int. % (bin middle)	Windspeed (m/s) (bin middle)															
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Total
6							1			1	1	1				4
8									1				1			2
10								1								1
12									1							1
14				1												1
16						1										1
18						1										1
22			1													1
26			1													1
28	1															1
	1		2	1		2	1	1	2	1	1	1	1			14

Normalisation of flatwise bending moments

Normalised maximum instantaneous flatwise loads: 3
Normalised minimum instantaneous flatwise loads: -2

Analysis conducted using normalised flatwise loads: -3, +6

One year wind speed time history of 10min mean

Number of starts at V_{in}: 404
Number of stops at V_{in}: 404
Number of starts at V_{out}: 43
Number of stops at V_{out}: 43

Normalisation of cyclic content (rotational speed)

For the normalisation the reference number of rotor revolutions was defined as 16rpm constant rotor speed as agreed in the group. The number of annual revolutions is 1.08 E7. This results in a normalization factor of f = 0.779.

Range mean matrix

In the 64 x 64range mean matrix of ECN the values of the range and the mean are the bin middle. The mean values range from -3 to 6. The values of the range range from 0 to 9.

Turbine 500 kW /37 (Name of manufacturer and type of turbine withheld)

General Characteristics

TURBINE MAIN SPECIFICATIONS	
Rotor diameter	37m
Rated Power Output	500 kW
Power control	Stall control
Rotor speed	Constant speed 30RPM
Number of Blades	3
Rotor position	upwind
Hub height	35m

Description of The Site

The WT is installed on an island in a complex terrain site, while the landscape in the vicinity of the wind turbine is bare with sparse, low laying vegetation and small rocks. The typical roughness length has been estimated at about 0.10m.

A reference meteo mast was also erected in the site, approximately two rotor diameters (D_{rotor} = 37m) away from the wind turbine at a SSW direction.

Acceptable sector for load measurements: 275º-330º

Description of Amount and Quality of Available Data

Following table presents the normal power production capture matrix. In this table the three turbulence intensity bins in italic, namely containing data for turbulence intensity from 6% to 12% are used for the data analysis.

capture matrix for normal power production

Wind (m/s) ⇒ I (%) ⇓	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25
2-4	0	9	12	30	48	66	49	44	17	20	8	3	0	0	1	0	0	0	0	0	0	0
4-6	0	11	22	11	69	92	99	103	91	70	50	61	28	27	24	5	0	0	1	3	0	0
6-8	*1*	*18*	*33*	*44*	*134*	*162*	*168*	*197*	*225*	*211*	*233*	*259*	*212*	*184*	*132*	*61*	*14*	*10*	*10*	*2*	*0*	*0*
8-10	*0*	*18*	*65*	*146*	*236*	*255*	*278*	*253*	*254*	*309*	*406*	*459*	*412*	*374*	*250*	*78*	*26*	*18*	*7*	*0*	*0*	*0*
10-12	*0*	*23*	*72*	*114*	*165*	*218*	*157*	*180*	*188*	*320*	*355*	*391*	*321*	*251*	*124*	*24*	*3*	*1*	*0*	*0*	*0*	*0*
12-14	0	13	39	66	75	65	57	56	71	65	89	90	47	26	11	2	1	0	0	0	0	0
14-16	0	7	16	27	19	17	18	16	10	8	7	8	4	2	0	0	0	0	0	0	0	0
16-18	0	1	9	5	4	6	8	11	2	1	0	0	0	0	0	0	0	0	0	0	0	0
18-20	0	0	1	3	3	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0

Therefore, the resulting capture matrix of data used in the analysis of turbulence bin of 6% width is shown in the following table

Wind (m/s) ⇒ I (%) ⇓	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25
6-12	1	59	170	304	535	635	603	630	667	840	994	1109	945	809	506	163	43	29	17	**2**	0	0

Missing data for wind bins 23-24 and 24-25 were substituted by data in wind bin 22-23 shown in bold.
No transient manoeuvres (starts/stops/ E-stops) are included in the database

Normalisation of flatwise bending moments

Analysis conducted using normalised flatwise loads: -3, +6

One year wind speed time history of 10min mean

Annual cumulated Rainflow load spectra

Used Weibull with A=9.59 and C=2.0
Rainflow parameters: Hysteresis = 1.1, counting of residuals as full cycles

Normalisation of cyclic content (rotational speed)

The cycles were normalized in order to meet the reference rotational speed of 16rpm.

Add low cyclic loads for each turbine and transient loads

Results from this procedure are given in files named "flap_mr_ver1.dat" and "Flap_cum_ver1.dat" for flapwise loading. Specifically, the "flap_mr_ver1.dat" file contains the number of full cycles in a mean range table. The format of the file is shown in following table:

		Mean bin⇒	1	2	3	4	5	…	64
		Mean bin from	-3.000	-2.859	…				
Range bin⇓	Range bin from	Mean bin to Range bin to	-2.859	-2.719	…				
1	0.000	0.141	data	data	…				
2	0.141	0.282	…						
3	0.282	0.422							
4	…	…							
5									
…									
64									

The file "Flap_cum_ver1.dat" contains in columns:
Column A: Range bin
Column B: Range bin from
Column C: Range bin to
Column D: cumulative full cycles

Turbine 1.3MW (Name of manufacturer and type of turbine withheld)

General Characteristics

TURBINE MAIN SPECIFICATIONS	
Rotor diameter	62.5m
Rated Power Output	1320 kW
Power control	Stall control
Rotor speed	Constant speed/two speeds
Number of Blades	3
Rotor position	upwind
Hub height	61.4m

Description of The Site

Towards the north and south there are higher hills forcing the wind to blow through a physical channel oriented along an east-west direction. Obstacles to be taken into account are a one-story building to the north-northwest of the wind turbine, a stopped wind turbine to the north, and three operating wind turbines to the south. The surrounding topography is complex. Terrain roughness length is estimated to be on the order of 20 cm.

Acceptable sector for load measurements: 54º-89º & 251º-281º
Mean turbulence in sector: 11.68%

Description of Amount and Quality of Available Data

Following table presents the normal power production capture matrix. In this table the three turbulence intensity bins in italic, namely containing data for turbulence intensity from 6% to 12% are used for the data analysis.

capture matrix for normal power production

Wind (m/s) ⇒ I (%) ⇓	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25
< 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	0	0	0	2	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0
4-6	2	0	0	0	1	0	2	1	2	2	7	11	11	4	0	2	0	0	0	0	0	0
6-8	*5*	*3*	*1*	*14*	*9*	*15*	*8*	*13*	*23*	*22*	*50*	*54*	*55*	*20*	*2*	*1*	*0*	*1*	*2*	*0*	*0*	*0*
8-10	*5*	*8*	*16*	*25*	*44*	*29*	*22*	*27*	*26*	*62*	*89*	*89*	*46*	*19*	*12*	*9*	*0*	*0*	*1*	*0*	*0*	*0*
10-12	*5*	*7*	*23*	*36*	*21*	*27*	*28*	*48*	*43*	*52*	*43*	*29*	*23*	*20*	*11*	*3*	*0*	*0*	*0*	*0*	*0*	*0*
12-14	8	13	26	25	10	23	27	34	34	27	9	7	5	3	1	2	3	0	0	0	0	0
14-16	9	10	14	20	10	12	11	8	6	5	0	0	1	3	3	2	1	0	0	0	0	0
16-18	11	5	9	15	6	7	6	2	2	1	1	1	0	3	0	1	0	0	0	0	0	0
20-22	11	14	6	5	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-24	10	7	7	4	3	2	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
24-26	10	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26-28	5	2	0	2	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
28-30	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Therefore, the resulting capture matrix of data used in the analysis of turbulence bin of 6% width is shown in the following table

Wind (m/s) ⇒ I (%) ⇓	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25
6-12	15	18	40	75	74	71	58	88	92	136	182	172	124	59	25	13	0	1	**3**	0	0	0

Missing data for wind bins 19-20, 22-23, 23-24 and 24-25 were substituted by data in wind bin 21-22 shown in bold.

Capture of transient manoeuvres

The capture matrix (actual measured events/wind speed) for normal transient events

Normal start-up and shut-down events		
Event	$V_{in} < V < V_r - 2$ m/s	$V > V_r$
Start-up	13	8
Normal shut-down	12	3

Capture matrix for other than normal transient events

Other transient events	
Event	**Number of events**
Emergency shut-down	3

Normalisation of flatwise bending moments

Normalised maximum instantaneous flatwise loads: 6
Normalised minimum instantaneous flatwise loads: -1

Analysis conducted using normalised flatwise loads: -3, +6

One year wind speed time history of 10min mean

Number of starts at V_{in}: 493
Number of stops at V_{in}: 493
Number of starts at V_{out}: 12
Number of stops at V_{out}: 12
Emergency stops: 40

Annual cumulated Rainflow load spectra

Used Weibull with A=9.59 and C=2.0
Rainflow parameters: Hysteresis = 1.1, counting of residuals as full cycles

Normalisation of cyclic content (rotational speed)

For the normalisation the reference number of rotor revolutions was defined as 16rpm constant rotor speed as agreed in the group.

Add low cyclic loads for each turbine and transient loads

Results from this procedure are given in files named "mean_range_ver1.txt" and "cumulative_range_ver1.txt" for flapwise loading. Specifically, the "mean_range_ver1.txt" file contains the number of full cycles in a mean range table. The format of the file is shown in the following table:

		Mean bin⇒	1	2	3	4	5	…	64
		Mean bin from	-3.000	-2.859	…				
		Mean bin to	-2.859	-2.719	…				
Range bin⇓	Range bin from	Range bin to							
1	0.000	0.141	data	data	…				
2	0.141	0.282	…						
3	0.282	0.422							
4	…	…							
5									
…									
64									

The file "cumulative_range_ver1.txt" contains in columns:
Column A: Range bin
Column B: Range bin from
Column C: Range bin to
Column D: cumulative full cycles

Turbine >3MW (Name of manufacturer and type of turbine withheld)

General Characterictics

TURBINE MAIN SPECIFICATIONS	
Rotor diameter	104m
Rated Power Output	>3 MW
Power Control	Pitch Control / variable
Rotor speed (range / 1st 2nd speed)	8.5 – 13.5
Number of Blades	3
Rotor position	Upwind (luv)
Hub height	100 m
Prototype / Serial WEC	Prototype
Cut-in Wind Speed	3,5 m/s
Rated Wind Speed	14.3 m/s
Cut-out Wind Speed	25 m/s

Site description

- The turbine is sited in a wind park in industrial area featuring flat coastal terrain
- Wake inflow conditions caused by neighbouring turbines reduce measurement sector to 212° - 315°.
- The mean turbulence of the sector is 8.2%
- The distance between meteorological-mast and turbine is 5.17 rotor diameter.

Instrumentation

Load Quantity	Instrumentation	Remarks
Blade Root Flap Bending	Full Strain Gauge Bridge	Distance to blade flange: 700mm
Blade Root Lead-Lag Bending	Full Strain Gauge Bridge	Distance to blade flange: 700mm

Table of load quantities measured and remarks.

Quantity	Instrumentation	Remarks
Wind Speed	Anemometer	Measured at Hub Height, Met.-Mast
Wind Speed	Anemometer	Measured on Nacelle
Wind Direction	Wind Vane	Wind Direction at Hub Height
Electrical Power	Power Transducer	Cabinet

Table of meteorological / operatiuonal quantities measured and remarks.

Description of Amount and Quality of Available Data

Following table presents the normal power production capture matrix from the measurement sector. The start and stop data sets were not classified into sectors.

V(m/s)	0	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	>21.5
I(%)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5	V out
0- <3																				
3- 5																				
5- 7																				
7- 9	**5**	**10**	**18**	**24**	**30**	**35**	**51**	**26**	**16**	**26**	**8**	**6**	**1**	**2**			**1**			
9- 11	**7**	**31**	**27**	**25**	**18**	**33**	**41**	**25**	**18**	**32**	**35**	**14**	**4**	**6**	**1**					
11- 13	**5**	**26**	**23**	**15**	**31**	**23**	**27**	**19**	**14**	**13**	**17**	**5**	**4**	**4**	**4**	**2**	**1**			
13- 15																				
15- 17																				
17- 19																				
19- 21																				
21- 23																				
23- 25																				
25- 27																				
27- 29																				
>29																				
	17	67	68	64	79	91	119	70	48	71	60	25	9	12	5	2	2	0	0	0

Datasets :	**809**
mean Turbulence:	**9.94**

Three emergency stop transients were recorded at 3, 8 and 9 m/s.

Therefore, the resulting capture matrix of data used in the analysis of turbulence bin of 7-13% width is shown in the following table

V(m/s)	0	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	>21.5
I(%)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5	V out
0- <3																				
3- 5																				
5- 7																				
7- 9	5	10	18	24	30	35	51	26	16	26	8	6	1	2	2	2	3	3	3	12
9- 11	7	31	27	25	18	33	41	25	18	32	35	14	4	6	1	1	1	1	1	4
11- 13	5	26	23	15	31	23	27	19	14	13	17	5	4	4	4	6	7	7	7	28
13- 15																				
15- 17																				
17- 19																				
19- 21																				
21- 23																				
23- 25																				
25- 27																				
27- 29																				
>29																				
	17	67	68	64	79	91	119	70	48	71	60	25	9	12	7	9	11	11	11	44

Datasets :	**893**
mean Turbulence:	**10.00**

TU 8:Missing data for wind bins above 16 m/s were substituted/ complemented by data from wind bin 16 shown in ***blue italics*** (one data set in wind bin 18m/s + 2 from wind bin 16 m/s)

TU 10:Missing data for wind bins above 17 m/s were substituted by data from wind bin 17 shown in ***blue italics***.

TU 12:Missing data for wind bins above 17 m/s were substituted by data in wind bin 17 shown in ***blue italics***.

Used transient manoeuvres

The capture matrix (actual measured events/wind speed) for normal transient events

Normal start-up and shut-down events		
Event	$V_{in} < V < V_r - 2$ m/s	$V > V_r$
Start-up		-
Normal shut-down		-

Capture matrix for other than normal transient events

Other transient events	
Event	**Number of events**
Emergency shut-down	

Normalisation of flatwise bending moments

Normalised maximum instantaneous flatwise loads: 4
Normalised minimum instantaneous flatwise loads: -2

Analysis conducted using normalised flatwise loads: -3, +6

Annual cumulated Rainflow load spectra

Used Weibull with A=9.59 and C=2.0
Rainflow parameters: Hysteresis = 1.1x bin width = 0.15469, counting of residuals as full cycles

Normalisation of cyclic content (rotational speed)

For the normalisation the reference number of rotor revolutions was defined as 16rpm constant rotor speed as agreed in the group.
Normalization Factor Used: 1,560165

Add low cyclic loads for each turbine and transient loads

Load Cycles from Annual Wind Speed Time History of 10min-Averages According to RISØ-Method:

Based on the annual wind speed time series supplied by DEWI a load time series of Min / Max loads of length 99460 was created and Rainflow-counted

Load Cycles from Starts and Stops / Emergency Stops / Other Transients:

Number of starts at V_{in}: 493
Number of stops at V_{in}: 493
Number of starts at V_{out}: 12
Number of stops at V_{out}: 12
Emergency stops: 40

ANNEX III
NEW WISPER RANGE PAIR SPECTRA

NEW WISPER RANGE PAIR SPECTRUM

		For Comparison to WISPER			
Bin	Load in i-th Bin (middle of bin)	strain	stress	cumulative frequency - NEW WISPER	counts
1	0.0703125	1.26828E-05	3.42E-01	47702.0	0.0
2	0.2109375	3.80484E-05	1.03E+00	47702.0	0.0
3	0.3515625	0.000063414	1.71E+00	47702.0	0.0
4	0.4921875	8.87796E-05	2.40E+00	47702.0	0.0
5	0.6328125	0.000114145	3.08E+00	47702.0	0.0
6	0.7734375	0.000139511	3.77E+00	47702.0	0.0
7	0.9140625	0.000164876	4.45E+00	47702.0	0.0
8	1.0546875	0.000190242	5.14E+00	47702.0	0.0
9	1.1953125	0.000215608	5.82E+00	47702.0	0.0
10	1.3359375	0.000240973	6.51E+00	47702.0	0.0
11	1.4765625	0.000266339	7.19E+00	47702.0	0.0
12	1.6171875	0.000291704	7.88E+00	47702.0	0.0
13	1.7578125	0.00031707	8.56E+00	47702.0	14042.0
14	1.8984375	0.000342436	9.25E+00	33660.0	9562.0
15	2.0390625	0.000367801	9.93E+00	24098.0	6782.0
16	2.1796875	0.000393167	1.06E+01	17316.0	4867.0
17	2.3203125	0.000418532	1.13E+01	12449.0	3342.0
18	2.4609375	0.000443898	1.20E+01	9107.0	2277.0
19	2.6015625	0.000469264	1.27E+01	6830.0	1711.0
20	2.7421875	0.000494629	1.34E+01	5119.0	1333.0
21	2.8828125	0.000519995	1.40E+01	3786.0	935.0
22	3.0234375	0.00054536	1.47E+01	2851.0	609.0
23	3.1640625	0.000570726	1.54E+01	2242.0	574.0
24	3.3046875	0.000596092	1.61E+01	1668.0	356.0
25	3.4453125	0.000621457	1.68E+01	1312.0	306.0
26	3.5859375	0.000646823	1.75E+01	1006.0	206.0
27	3.7265625	0.000672188	1.81E+01	800.0	140.0
28	3.8671875	0.000697554	1.88E+01	660.0	131.0
29	4.0078125	0.00072292	1.95E+01	529.0	121.0
30	4.1484375	0.000748285	2.02E+01	408.0	78.0
31	4.2890625	0.000773651	2.09E+01	330.0	48.0
32	4.4296875	0.000799016	2.16E+01	282.0	59.0
33	4.5703125	0.000824382	2.23E+01	223.0	50.0
34	4.7109375	0.000849748	2.29E+01	173.0	16.0
35	4.8515625	0.000875113	2.36E+01	157.0	32.0
36	4.9921875	0.000900479	2.43E+01	125.0	44.0
37	5.1328125	0.000925844	2.50E+01	81.0	16.0
38	5.2734375	0.00095121	2.57E+01	65.0	6.0
39	5.4140625	0.000976576	2.64E+01	59.0	5.0
40	5.5546875	0.001001941	2.71E+01	54.0	22.0
41	5.6953125	0.001027307	2.77E+01	32.0	23.0
42	5.8359375	0.001052672	2.84E+01	9.0	1.0
43	5.9765625	0.001078038	2.91E+01	8.0	1.0
44	6.1171875	0.001103404	2.98E+01	7.0	4.0
45	6.2578125	0.001128769	3.05E+01	3.0	1.0
46	6.3984375	0.001154135	3.12E+01	2.0	1.0
47	6.5390625	0.0011795	3.18E+01	1.0	1.0
48	6.6796875	0.001204866	3.25E+01	0.0	0.0
49	6.8203125	0.001230232	3.32E+01	0.0	0.0
50	6.9609375	0.001255597	3.39E+01	0.0	0.0

51	7.1015625	0.001280963	3.46E+01	0.0	0.0
52	7.2421875	0.001306328	3.53E+01	0.0	0.0
53	7.3828125	0.001331694	3.60E+01	0.0	0.0
54	7.5234375	0.00135706	3.66E+01	0.0	0.0
55	7.6640625	0.001382425	3.73E+01	0.0	0.0
56	7.8046875	0.001407791	3.80E+01	0.0	0.0
57	7.9453125	0.001433156	3.87E+01	0.0	0.0
58	8.0859375	0.001458522	3.94E+01	0.0	0.0
59	8.2265625	0.001483888	4.01E+01	0.0	0.0
60	8.3671875	0.001509253	4.07E+01	0.0	0.0
61	8.5078125	0.001534619	4.14E+01	0.0	0.0
62	8.6484375	0.001559984	4.21E+01	0.0	0.0
63	8.7890625	0.00158535	4.28E+01	0.0	0.0
64	8.9296875	0.001610716	4.35E+01	0.0	0.0

From Overall Annual Spetrum to Recounted Range Pair Spectrum

NEW WISPER RAINFLOW MATRIX			ANNUAL Range Pair	ANNUAL Range Pair Cumulative	REDUCED 2Months Range Pair	REDUCED 2Months Range Pair Cumulative	Recounted from TS reconstruction	difference to original NEW WIPSER
Range		Bin	counts	counts	counts	counts	counts	
0	0.140625	1	0	286173	0	47702	47735	33
0.140625	0.28125	2	0	286173	0	47702	47735	33
0.28125	0.421875	3	0	286173	0	47702	47735	33
0.421875	0.5625	4	0	286173	0	47702	47735	33
0.5625	0.703125	5	0	286173	0	47702	47735	33
0.703125	0.84375	6	0	286173	0	47702	47735	33
0.84375	0.984375	7	0	286173	0	47702	47735	33
0.984375	1.125	8	0	286173	0	47702	47735	33
1.125	1.265625	9	0	286173	0	47702	47735	33
1.265625	1.40625	10	0	286173	0	47702	47735	33
1.40625	1.546875	11	0	286173	0	47702	47735	33
1.546875	1.6875	12	0	286173	0	47702	47735	33
1.6875	1.828125	13	84249	286173	14042	47702	47735	33
1.828125	1.96875	14	57370	201924	9562	33660	33692	32
1.96875	2.109375	15	40691	144554	6782	24098	24130	32
2.109375	2.25	16	29201	103863	4867	17316	17346	30
2.25	2.390625	17	20053	74662	3342	12449	12477	28
2.390625	2.53125	18	13660	54609	2277	9107	9131	24
2.53125	2.671875	19	10267	40949	1711	6830	6852	22
2.671875	2.8125	20	7999	30682	1333	5119	5141	22
2.8125	2.953125	21	5611	22683	935	3786	3803	17
2.953125	3.09375	22	3653	17072	609	2851	2865	14
3.09375	3.234375	23	3443	13419	574	2242	2255	13
3.234375	3.375	24	2137	9976	356	1668	1679	11
3.375	3.515625	25	1838	7839	306	1312	1321	9
3.515625	3.65625	26	1237	6001	206	1006	1012	6
3.65625	3.796875	27	839	4764	140	800	803	3
3.796875	3.9375	28	784	3925	131	660	662	2
3.9375	4.078125	29	723	3141	121	529	530	1
4.078125	4.21875	30	465	2418	78	408	409	1
4.21875	4.359375	31	289	1953	48	330	332	2
4.359375	4.5	32	353	1664	59	282	284	2
4.5	4.640625	33	297	1311	50	223	226	3
4.640625	4.78125	34	93	1014	16	173	177	4
4.78125	4.921875	35	192	921	32	157	161	4
4.921875	5.0625	36	261	729	44	125	128	3
5.0625	5.203125	37	98	468	16	81	84	3
5.203125	5.34375	38	38	370	6	65	68	3
5.34375	5.484375	39	28	332	5	59	61	2
5.484375	5.625	40	133	304	22	54	56	2
5.625	5.765625	41	135	171	23	32	34	2
5.765625	5.90625	42	5	36	1	9	11	2
5.90625	6.046875	43	1	31	1	8	10	2
6.046875	6.1875	44	22	30	4	7	9	2
6.1875	6.328125	45	3	8	1	3	5	2
6.328125	6.46875	46	3	5	1	2	4	2
6.46875	6.609375	47	2	2	1	1	3	2
6.609375	6.75	48	0	0	0	0	2	2
6.75	6.890625	49	0	0	0	0	2	2
6.890625	7.03125	50	0	0	0	0	2	2
7.03125	7.171875	51	0	0	0	0	2	2
7.171875	7.3125	52	0	0	0	0	2	2
7.3125	7.453125	53	0	0	0	0	2	2
7.453125	7.59375	54	0	0	0	0	2	2
7.59375	7.734375	55	0	0	0	0	0	0
7.734375	7.875	56	0	0	0	0	0	0
7.875	8.015625	57	0	0	0	0	0	0
8.015625	8.15625	58	0	0	0	0	0	0

8.15625	8.296875	59	0	0	0	0	0	0
8.296875	8.4375	60	0	0	0	0	0	0
8.4375	8.578125	61	0	0	0	0	0	0
8.578125	8.71875	62	0	0	0	0	0	0
8.71875	8.859375	63	0	0	0	0	0	0
8.859375	9	64	0	0	0	0	0	0

Conversion Table from Normalized Load to Discrete Bins

6	42.6666667	64		9	64	
5.859375	41.6666667	63		8.859375	63	
5.71875	40.6666667	62		8.71875	62	
5.578125	39.6666667	61		8.578125	61	
5.4375	38.6666667	60		8.4375	60	
5.296875	37.6666667	59		8.296875	59	
5.15625	36.6666667	58		8.15625	58	
5.015625	35.6666667	57		8.015625	57	
4.875	34.6666667	56		7.875	56	
4.734375	33.6666667	55		7.734375	55	
4.59375	32.6666667	54		7.59375	54	
4.453125	31.6666667	53		7.453125	53	
4.3125	30.6666667	52		7.3125	52	
4.171875	29.6666667	51		7.171875	51	
4.03125	28.6666667	50		7.03125	50	
3.890625	27.6666667	49		6.890625	49	
3.75	26.6666667	48		6.75	48	
3.609375	25.6666667	47		6.609375	47	
3.46875	24.6666667	46		6.46875	46	
3.328125	23.6666667	45		6.328125	45	
3.1875	22.6666667	44		6.1875	44	
3.046875	21.6666667	43		6.046875	43	
2.90625	20.6666667	42		5.90625	42	
2.765625	19.6666667	41		5.765625	41	
2.625	18.6666667	40		5.625	40	
2.484375	17.6666667	39		5.484375	39	
2.34375	16.6666667	38		5.34375	38	
2.203125	15.6666667	37		5.203125	37	
2.0625	14.6666667	36		5.0625	36	
1.921875	13.6666667	35		4.921875	35	
1.78125	12.6666667	34		4.78125	34	
1.640625	11.6666667	33		4.640625	33	
1.5	10.6666667	32		4.5	32	
1.359375	9.66666667	31		4.359375	31	
1.21875	8.66666667	30		4.21875	30	
1.078125	7.66666667	29		4.078125	29	
0.9375	6.66666667	28		3.9375	28	
0.796875	5.66666667	27		3.796875	27	
0.65625	4.66666667	26		3.65625	26	
0.515625	3.66666667	25		3.515625	25	
0.375	2.66666667	24		3.375	24	
0.234375	1.66666667	23		3.234375	23	
0.09375	0.66666667	22		3.09375	22	
-0.046875	-0.33333333	21		2.953125	21	
-0.1875	-1.33333333	20		2.8125	20	
-0.328125	-2.33333333	19		2.671875	19	
-0.46875	-3.33333333	18		2.53125	18	
-0.609375	-4.33333333	17		2.390625	17	
-0.75	-5.33333333	16		2.25	16	
-0.890625	-6.33333333	15		2.109375	15	
-1.03125	-7.33333333	14		1.96875	14	
-1.171875	-8.33333333	13		1.828125	13	
-1.3125	-9.33333333	12		1.6875	12	
-1.453125	-10.3333333	11		1.546875	11	
-1.59375	-11.3333333	10		1.40625	10	
-1.734375	-12.3333333	9		1.265625	9	
-1.875	-13.3333333	8		1.125	8	
-2.015625	-14.3333333	7		0.984375	7	
-2.15625	-15.3333333	6		0.84375	6	
-2.296875	-16.3333333	5		0.703125	5	
-2.4375	-17.3333333	4		0.5625	4	
-2.578125	-18.3333333	3		0.421875	3	

-2.71875	-19.3333333	2		0.28125	2	
-2.859375	-20.3333333	1		0.140625	1	
-3	-21.3333333	0		0	0	