2. EDITION

EXPERT GROUP STUDY
ON

RECOMMENDED PRACTICES FOR WIND TURBINE TESTING AND EVALUATION

3. FATIGUE LOADS

2. EDITION 1990

Submitted to the Executive Committee
of the International Energy Agency Programme
for
Research and Development
on Wind Energy Conversion Systems

RECOMMENDED PRACTICES FOR WIND TURBINE TESTING

3. FATIGUE LOADS

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1. INTRODUCTION

The procedures needed for testing and evaluation of wind turbines must encompass aspects ranging from: energy production, quality of power, reliability, durability and safety as well as cost effectiveness or economics, noise characteristics, impact on environment and electromagnetic interference. The development of internationally agreed upon procedures for testing and evaluation for each of these areas is needed to aid the industrial development of wind turbines while strengthening confidence in the technology and preventing chaos in the market.

It is the purpose of the proposed recommended practices for wind turbine testing and evaluation to contribute to the development of such internationally approved procedures. The IEA expert committee will pursue this effort by periodically holding meetings of experts, to define and refine consensus procedures in each of the following areas:

1. Power performace [1]
2. Cost of energy from WECS [2]
3. Fatigue loads
4. Acoustics [3]
5. Electromagnetic interference [4]
6. Safety and reliability [5]
7. Quality of power [6]
8. Glossary of terms [7]

This paper addresses the third area of Fatigue Loads and is a revision of the paper "Recommended Practices for Wind Turbine Testing and Evaluation: 3. Fatigue Characteristics", 1st edition 1984.

The expert committee will seek to gain approval of the recommended procedures in each member country through the IEA agreements. The recommendations shall be regularly reviewed and areas in need of further investigation shall be identified.

2. SCOPE

This document describes recommended practices for the evaluation of the fatigue loads on an electricity producing horizontal-axis wind turbine by means of measurements. Fatigue loads are understood to be frequently occurring cyclic loads which may cause cumulative high-cycle fatigue damage in the load-carrying wind turbine components. The aim is to provide a standard method of determining the fatigue loads during different modes of operation and thus provide measured data with which fatigue damage rates and fatigue lifetime can be estimated.

The fatigue loading characteristics, pertaining to the estimation of fatigue lifetime, are expressed in terms of the duty cycle which characterises the number, duration and succession of operational modes, as well as the fatigue loads from each mode of operation. The resulting primary description of the fatigue loads is expressed in terms of fatigue load cycle spectra based on a rain flow cycle counting of the load time series recordings. This representation is especially well suited for a fatigue damage calculation using the Palmgren-Miner linear damage rule and the S-N curve formulation of the material fatigue characteristics.

Alternatively, the fatigue loading chracteristics can be obtained using on-line monitoring. Data are continuously reduced by counting and storing fatigue causing load cycles. The monitoring should continue over a sufficiently long time period for the number and occurrences of the load cases to be representative. A period of 10 percent of the lifetime is estimated as sufficient. The method is not recommended due to frequent problems with the reliability of the measurement system and difficulties with identifying and removing faulty data. In addition the results can only be extrapolated with difficulty to a different site.

The main scope of the recommended practices is the determination of the fatigue load characteristics of the wind turbine. A limited number of strain measuring points is considered which is sufficient to determine the fundamental loads, blade bending moments near the root, and the forces and moments transmitted from the wind turbine rotor. The translation of these loads into stresses at critical details of the construction (bolts, weldings etc.) has to be made for each particular wind turbine and is therefore not dealt with in detail. A possible procedure, however, is outlined in Appendix B and C for high-cycle fatigue. Furthermore, specific points relating to the material in calculating the fatigue life and damage have not been addressed.

It should be noted that the verfication of adequate fatigue life can only partially be based on the proposed set of measurements. A number of design load cases are difficult, either because of rarity of occurence or undesirability to include them in the tests such as the extreme design wind conditions, certain emergency load cases, or operational failures. Such load cases should be included in the verfication by means of calculations.

3. DEFINITIONS AND UNITS

Units - Numerical values reported are to be given in metric Systemes Internationale (SI) units. If desired they may be followed in parenthesis by the local units.

Availability - The duration of energy production operation time divided by the potential duration, i.e. the duration of periods with an averaged wind speed in the operation range. The availability is measured in percent.

Average wind speed V_{av} - The average value over 10 minutes of the wind speed at hub height.

Cut-in wind speed V_{in} - The wind speed at which the wind turbine starts to produce usable power.

Cut-out wind speed V_{out} - The maximum wind speed at which the wind turbine is designed to produce usable power.

Duty cycle - A wind turbine duty cycle is a repetitive period of operation which is characterised by a typical succession and duration of modes of operation.

Time series recording - Measurements of a number of wind turbine parameters for a limited period of time during a specific mode of operation.

Fatigue loads - Cyclic loads which cause accumulative damage in the material of the structural components and eventually lead to structural failure. Failure takes place by the initiation and propagation of a crack until it becomes unstable and propagates suddenly to failure. Fatigue loads are well below the static failure levels.

High-cycle fatigue - A term to characterise the fatigue phenomenon when the cyclic loads are of such a magnitude that more than about 10000 cycles are required to produce failure.

Mode of operation - A mode of operation is a specific operational procedure of the wind turbine (start, stop, normal operation, stand-still) under well defined external conditions.

Range - The peak to peak value of a cyclic signal, i.e. twice the amplitude of a sinusoidal signal.

Rated wind speed V_{rated} - The lowest averaged wind speed at which the wind turbine produces the nominal power output. If the definition is not applicable use $V_{rated} = (V_{in} + V_{out})/2$.

WECS - Wind energy conversion system.

Wind turbine - A rotating machine including its support structure for converting the kinetic energy of the wind to another form of energy.

4. TESTING METHODOLOGY

4.1 General considerations

The objective of the testing is to characterise the fatigue loading situation of the wind turbine in question in terms of

- Environmental conditions at the site during the testing.
- The duty cycles of the wind turbine as experienced during automatic operation of the turbine at the test site.
- Fundamental fatigue loads experienced during well-defined modes of operation.

4.2 Environmental conditions

The environmental conditions for the turbine under test should be well documented. It is recommended that the documemtation comprises:

- A general specification of the terrain at the test site which consists of a description of the main topographical features and the altitude of the region where the test site is located, as well as a detailed description of surface characteristics (roughness, obstacles, terrain inhomogenieties) in each of 8 directional sectors for a distance of up to 1 km from the turbine.
- The documentation of the atmospheric conditions should contain information on the averaged wind speed at hub height, the turbulence intensity and the mean and the standard deviation of the wind direction. Additional useful, but not essential, information is the vertical wind speed gradient, the temperature, the temperature gradient and the air pressure.

4.3 Duty cycles

The wind turbine's duty cycle describes the sequence and the duration of the modes of operation during the life of the turbine in terms of the operational statistics, see 5.2.1. This is illustrated in Fig. 4.3.1. Knowledge of the duty cycle is essential to the estimation of fatigue life from information on fatigue loads and damage rates for single modes of operation.

It is recommended that the duty cycle be specified by a sequence of parameters which define the mode of operation for consecutive 10 minute periods for a representative time span.

As a minimum, the number of starts and stops as well as the wind turbine status should be recorded for each 10 minute period, together with the minimum set of atmospheric parameters, see section 4.2.

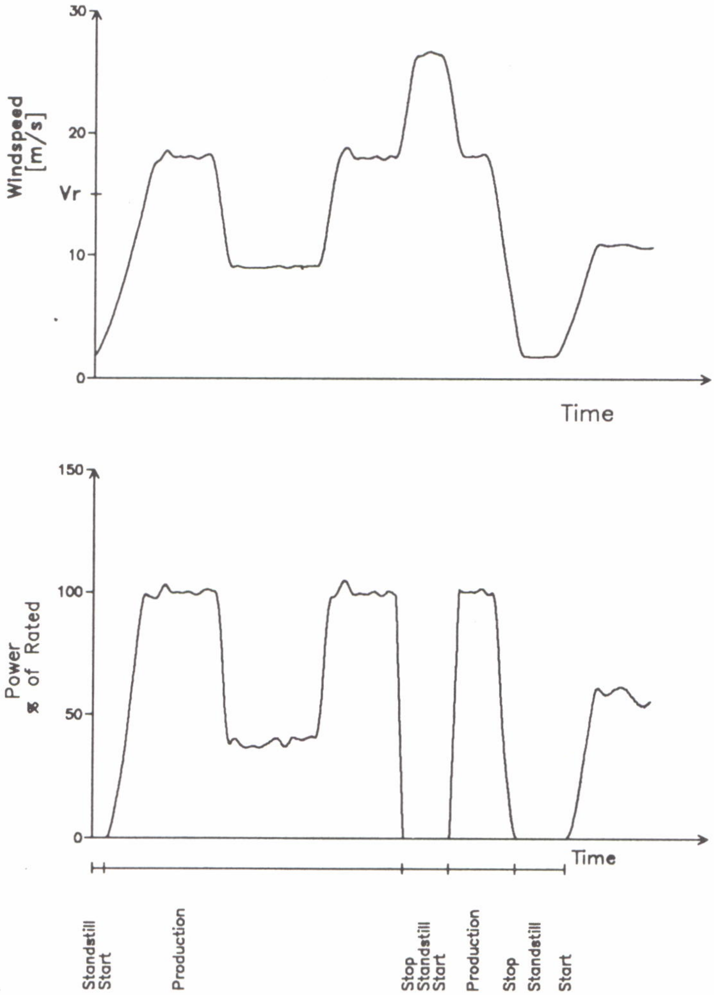

Fig 4.3.1 The sequence of the operational modes, the duty cycle.

In the description of the duty cycle it is recommended to include the full set of recorded atmospheric condition parameters specified in Table 2 of section 5.1.1 together with the number of starts of the yaw drive, the yaw and the pitch position and the duration of production operation and yawing.

The minimum as well as the recommended number of sensors with which to measure the duty cycle, are stated in section 5.1.

4.4 Time series recordings

A time series recording is the measurement of a number of atmospheric and wind turbine parameters with a high time- resolution for a limited period, preferably 10 minutes. The time series recordings to be carried out should reflect the various operational conditions that the wind turbine may experience during its life time.

The operational life of the wind turbine is divided into a finite set of modes of operation. Each of the modes of operation are investigated by means of time series recordings. In addition to normal operational modes where the wind turbine operation is determined by its own control system, a number of abnormal operation modes and a number of test modes are considered. The recommended time series recordings are listed in Table 1. Of these the normal operation load cases and the first two of the abnormal operation cases, emergency stop and free-running with air brakes, are considered essential. The corresponding modes of operation will be discussed in the next section.

TABLE 1. Time series recordings for fatigue loads evaluation

Mode of operation	Wind Speed
1. Normal operation	
Starting at cut-in	V_{in}
Starting at cut-out	V_{out}
Production operation	between V_{in} and V_{out}
Stopping at cut-in	V_{in}
Stopping at cut-out	V_{out}
Standstill/idling	$> V_{out}, < V_{in}$
2. Abnormal operation	
Emergency stop	V_{rated}, V_{out}
Free-running with air brakes	V_{out}
Yaw misalignment at +-30 degrees	$>V_{rated}$
3. Test and calibration operations	
Rotation of the rotor	$< V_{in}$

Not all modes of operation may be applicable for a specific type of wind turbine, and the number of modes should be adjusted to the type of wind turbine

4.5 Modes of operation

4.5.1 Normal operation

a) Starting the wind turbine. Starting is considered to be a possible fatigue critical event. Thus the connection of an electric generator to the grid can cause high transient loads in the drive train and the rotor blades.

During automatic operation the wind turbine will start at two different wind speeds

- at the cut-in wind speed V_{in}
- slightly below the cut-out wind speed V_{out}

Is is recommended that the two starting procedures are considered as different modes of operation (start at low wind speed and start at high wind speed) as they differ considerably in occurrence and aerodynamic loading.

b) Production operation. A substantial part of the fatigue damage is expected to be accumulated during operation when the wind turbine produces energy. Production operation modes are therefore considered fatigue critical events.

It is recommended that the operational wind speed range (V_{in} - V_{out}) is divided into wind speed intervals of 2 m/s. Unusual wind turbine types and wind conditions may justify another division. Each interval is considered a mode of operation. The measured signals should be divided into records of 10 minutes duration and be categorised according to the average wind speed of the record.

c) Stopping the wind turbine. During automatic operation the wind turbine will be stopped in a controlled manner at two wind speed levels

- slightly below the cut-in wind speed V_{in}
- at the cut-out wind speed V_{out}

The first procedure is frequently occurring but with moderate aerodynamic loads whereas the second is usually rare but can be associated with high aerodynamic loads. It is therefore recommended that the two procedures be treated as separate modes of operation (stop at low wind speed and stop at high wind speed).

d) Standstill/idling. During periods when the wind speed is outside the operational range, ie. below V_{in} or above V_{out}, a wind turbine is in its stand-still position or idling. Except for a wind turbine with an idling rotor outside the operating wind speed range, cyclic loads at wind speeds lower than V_{in} are expected to be insignificant. For wind turbines standing still the loads need not be measured if the wind speed is below V_{in}.

The measured signals during stand-still shall be divided into records of 10 minutes duration.

4.5.2 Abnormal operation

These time series recordings serve to quantify fatigue loads during rare but severe load conditions which are caused by an error in the wind turbine operational system (in contrast to the structural load-carrying system).

a) Emergency stop. In addition to the normal stop procedure most wind turbines have, for safety reasons, an emergency braking procedure or system which is activated when the controlled stop procedure fails or in the case of immediate danger. The emergency stop procedure may cause different and more severe loads than the normal stop procedure and should as such be treated as a separate mode of operation.

This mode of operation should be investigated at V_{rated} and V_{out}, since a fault detection may occur anytime, and normal stop procedure is more likely to fail at high wind speeds.

b) Free-running with air brakes. On a large number of wind turbines the secondary brake system consists of aerodynamic brakes which when activated limit the speed of rotation to a safe level. Their activation can cause large load transients and the loads during free-running may be different from production operation. This mode of operation may thus be critical for fatigue.

c) Yaw misalignment. Yaw misalignment which is the difference between the average wind direction and the direction of the rotor axis, causes cyclic aerodynamic blade loads. Especially for a stall-regulated wind turbine, yaw misalignment can contribute significantly to the fatigue loads.

It is recommended that time series recordings with a duration of 10 minutes are made for yaw misalignment angles of plus and minus 30 degrees.

4.5.3 Test and calibration operation

Time series recordings under the test operation mode serve to determine the magnitude of the gravity loading. The measurements are not directly applicable for fatigue estimates and may be omitted.

Rotation of the rotor. During the recording the rotor must be turning slowly (less than 10 percent of the nominal rotation speed) whilst the wind speed is well below V_{in}. The predominant load component is then the deterministic gravity loading.

If the blade pitch angle can be changed, it is recommended that recordings are performed with the pitch angle differing by 90 degrees, or if the range is less, at both ends of the range. At least 5 steady-state revolutions should be recorded.

Note. The recordings can be used to calibrate the blade bending moment signals, if the mass distribution of the blade is known.

5. DATA COLLECTION

5.1 Quantities to be measured

At both the recording of the duty cycle and the time series recordings a number of quantities must be measured. It is recommended that the recordings contain the quantities listed in Table 2 and use the listed number of sensors. Note that the list contains an absolute minimum set of quantities as well as the recommended set.

5.1.1 Atmospheric conditions

Wind speed. It is recommended that the wind speed is measured in a vertical array at 3 different heights: at hub height and at hub height +- the rotor radius. As a minimum the wind speed should be measured at hub height.

The wind speed measurement procedure and accuracy requirements are otherwise described in reference [1].

Unit: m/s

Wind direction. The wind direction instrument should have an accuracy of 2 degrees. The sensor should be located in the meteorological tower at hub height.

Unit: degrees from true North

Temperature. The air temperature at the site should be measured in accordance with common meteorological practice with an accuracy of 0.1 degree. The measurements of the temperature difference should be performed at two heights, preferably at the hub height +/- the rotor radius.

Unit: K

Air pressure. The air pressure measurements should be made in accordance with common meteorological practice. The accuracy should be 0.2 kPa.

Unit: Pascals

5.1.2 Wind turbine operation

Rotor speed. The rotor speed should be measured with an accuracy of 0.5 percent of the highest operational rotor speed over the full operating range.

Unit: rad/s

Rotor blade azimuth position. The measurements of the rotor blade angular position should make possible an accuracy of the blade azimuth angle of 3 degrees. For binning of the time series signals, the azimuth position should have an accuracy of at least one-half of the desired bin-width.

Unit: degrees

Table 2. Measured quantities for duty cycle and time series recordings

Measured quantity	Number of quantities to record			
	Duty cycle		Time series rec.	
	Recom.	Minimum	Recom.	Minimum
1. Atmospheric conditions				
Wind speed	3	1	3	1
Wind direction	1	1	1	1
Temperature	2		2	
Air pressure	1		1	
2. Wind turbine operation				
Rotor speed			1	
Azimuth position of the rotor blade			1	
Pitch angle	1		1*)	
Yaw angle	1		1	
Count of starts	1	1		
Count of stops	1	1		
Count of yaw drive starts	1			
Duration of production operation	1			
Duration of yawing	1			
Status	1	1		
Power output	1	1	1	1
3. Loads				
Blade bending moments			2*)	2**)
Main shaft bending moments (yaw, tilt)			2	2
Axial thrust			1	
Torque in the main shaft			1	1
Bending moment in the tower base			2	2
Torsion moment in the tower			1	

*) all blades, **) one blade. Not all quantities and sensors may be applicable for a specific type of wind turbine.

Pitch angle. The blade pitch angle should be measured with an accuracy of 0.3 degrees and a resolution of 0.1 degrees.

Unit: degrees

Yaw angle. The yaw angle is defined as the difference between the mean wind direction and the rotor shaft axis and should be measured with an accuracy of 1 degree.

Unit: degrees

Count of starts. The number of starts of the wind turbine, ie. the number of times the turbine goes from a stand-still or a idling position to production operation, should be counted during the measurement period in question.

Count of stops. The number of stops, ie. the number of times the turbine leaves the production mode to the stand-still or the idling mode, should be counted during the measurement period.

Count of yaw drive starts. The number of starts of the yaw drive, if present, during the measurement period should be counted.

Duration of production operation. The amount of time during the measurement period when the turbine produces energy, should be measured with an accuracy of 1 second.

Unit: sec.

Duration of yawing. The amount of time during the measurement period where the yaw drive is running, should be measured with an accuracy of 1 second.

Unit: sec.

Status. In the case where the wind turbine control system outputs the status (operating, nonoperating, error number etc.), the status should be recorded by the end of the measurement period.

Power output. The power output, if present, should be measured with an accuracy of 1 percent of the rated power.

Unit: Watt.

5.1.3 Loads

Blade bending moments. The bending moments near the blade root should be measured in two perpendicular directions, preferably corresponding to:

a) the flap-wise direction defined as out of plane of rotation

b) The lead-lag direction defined as in plane of rotation

The accuracy of the amplitude measurements should be better than 5 % of the maximum value of the amplitude and the accuracy of the mean value should be better than 10 percent of the maximum value of the amplitude.

Unit: Nm

Main shaft bending moments. The bending moments in the main shaft, preferably outside the first bearing, should be measured in two perpendicular directions.

The accuracy of the amplitude measurements should be better than 5 % of the maximum value of the amplitude and the accuracy of the mean value should be better than 10 percent of the maximum value of the amplitude.

Unit: Nm

Axial thrust. The axial thrust can be determined from measurements of the tilting moment from the rotor at the main shaft and the tower bending moment close to the base.

The accuracy of the amplitude measurements should be better than 5 % of the maximum value of the amplitude and the accuracy of the mean value should be better than 10 percent of the maximum value of the amplitude.

Unit: N.

Torque in the main shaft. The mechanical torque on the main shaft should be determined by direct measurements on the shaft. If no direct measure of the torque is available, it may be derived from the measurement of power and rotor speed by dividing the power by the rotor speed. Note that the power losses in the gearbox, bearings and generator should be accounted for.

The accuracy of the amplitude measurements should be better than 5 % of the maximum value of the amplitude and the accuracy of the mean value should be better than 10 percent of the maximum value of the amplitude.

Unit: Nm

Bending moment in the tower base. The bending moments in two perpendicular directions at the lowest part of the tower with a uniform geometry, should be measured.

The accuracy of the amplitude measurements should be better than 5 % of the maximum value of the amplitude and the accuracy of the mean value should be better than 10 % of the maximum value of the amplitude.

Unit: Nm

Torsion moment in the tower. The torsion moment on the tower should be measured.

The accuracy of the amplitude measurements should be better than 5 % of the maximum value of the amplitude and the accuracy of the mean value should be better than 10 % of the maximum value of the amplitude.

Unit: Nm

5.2 Recordings

5.2.1 Duty cycle

It is recommended that a measurement period of no less than 3 months be used to estimate the duty cycle of the wind turbine. During this period the turbine shall be in automatic operation, and all modes of operation shall be represented. For each consecutive 10 minute period the following minimum set of parameters should be recorded:

- Averaged wind speed at hub height
- Turbulence intensity at hub height
- Number of starts
- Number of stops
- Fault status at the end of the period
- Basic statistics of the power output

For a better environmental description of the duty cycle the parameters below can be included:

- Duration of production operation
- Number of starts of yaw drive
- Duration of yawing
- Basic statistics of the yaw error
- Basic statistics of the pitch angle
- Basic statistics of the vertical wind speed gradient
- Basic statistics of the wind direction
- Mean temperature and temperature gradient
- Richardson number
- Mean air pressure

By the basic statistics we understand the mean value, the standard deviation and the minimum and the maximum recorded value.

The signals from the wind speed, wind direction, temperature, pitch and yaw transducers should be read every 1-5 seconds, and the statistics should be calculated after each 10 minute period. The remaining signals are read at the end of the 10 minute period. Parameters corresponding to consecutive 10 minute periods should be stored in sequence.

The turbulence intensity is calculated from the wind speed at hub height as the standard deviation divided by the average of the wind speed.

The vertical wind gradient $\partial U/\partial z$ is determined from the wind speeds recorded at hub height +- rotor radius as the difference between the wind speed at the upper anemometer minus the wind speed at the lower divided by the vertical distance between the anemometers.

The Richardson number is a measure of the atmospheric stability or the atmospheric stratification. The atmospheric stability has a strong influence on the wind speed profile and on the intensity and the scale of the turbulence.

The Richardson number is calculated from the temperature and the wind speed measured at two heights, using

$$Ri = \frac{g\ (\gamma d \div \gamma)}{T\ (\partial u/\partial z)^2}$$

where g is the acceleration of gravity, $\gamma_d = 0.98$ C/100 m is the dry adiabatic lapse rate (decrease of temperature with height, γ is the prevailing lapse rate, and T is the temperature.

A negative value of Ri denotes unstable stratification, a positive value stable stratification while the atmosphere is neutral for Ri close to zero. At continental location far from the coast with thermally driven winds, non-neutral conditions appear also at higher wind speeds.

It is noted that the duty cycle recordings conveniently can be combined with power performance measurements, see reference [1].

5.2.2 Time series recordings

The measurements should be divided into records of 10 minutes duration. Preferably no less than 3 records for each normal mode of operation should be collected. In order to ensure that the data are representative and include possible variations in the atmospheric stability, it is recommended that a record is taken in the morning, at midday and in the evening for each normal mode of operation. The raw data should be stored.

5.2.3 Sample rates for time series recordings

The minimum sample rate for the time series recordings should be greater than

- 20 Hz
- 10 times the rotation frequency
- 10 times the lowest blade flapping resonance freqency
- 10 times the lowest tower bending resonance freqency

It is sufficient that the air pressure is recorded at the end of the 10 minute period.

6. ANALYSIS OF THE TEST DATA

The objective of the analysis is to present the measured fatigue loads in such a way that they can be used to estimate the fatigue life of the wind turbine components, see appendix B.

6.1 Duty cycles

The analysis of the duty cycle recordings should as a minimum contain:

- The number of occurrences of each mode of operation. Starts at wind speeds below the rated wind speed are referred to the load case starts at low wind speeds, starts at wind speeds above the rated wind speeds are referred to the load case starts at high wind speeds. Similarly for stops. The numbers should be normalised corresponding to a period of one year and 100 percent availability.
- The averaged wind speed distribution during the duty cycle measurement period determined by the method of bins with a bin width as given in Section 4.5.1 b).
- The average turbulence intensity for each mode of operation.

If the full recommended set of duty cycle parameters is recorded, the analysis should be complemented with:

- The availability in per cent.
- The duration of the yawing in percent of the operation time and the number of starts of the yaw drive.
- The observed distribution of yaw error below V_{rated} and above V_{rated}.
- For each wind speed bin the mean pitch angle and the basic statistics of the turbulence intensity, the vertical wind speed gradient and the Richardson number.
- Basic statistics of the 10 minute averaged air temperature and pressure.
- Observed distributions of

  · the yaw error below and above the rated wind speed
  · the averaged wind speed
  · the turbulence intensity
  · the Richardson number
  · the wind direction

  Note that the recorded parameters can be statistically dependent. The values to be used for the design extreme situation must be identified using correlation analysis.

6.2 Loads

6.2.1 Time series combination

The load signals from the time series recordings should be combined to give the following fundamental wind turbine loads:

1) Blade root lead-lag bending moment (moment vector perpendicular to the rotor plane) of the instrumented cross-section.
2) Blade root flapwise bending moment (moment vector in the rotor plane) of the instrumented cross-section.
3) Tilt rotor moment (horizontal moment vector) on the main shaft at the outer shaft support-bearing.
4) Yaw rotor moment (vertical moment vector) on the main shaft at the outer shaft support-bearing.
5) Mechanical torque on the main shaft.
6) Primary bending moment on the tower base (moment vector perpendicular to the rotor axis).
7) Secondary bending moment on the tower base (moment vector in the direction of the rotor axis).
8) Torsional moment in the tower.
9) Rotor thrust, the total force in the direction of the rotor axis delivered by the rotor to the main shaft at the hub.
10) Side force, the total horizontal force perpendicular to the rotor axis delivered by the rotor to the main shaft at the hub.

If fatigue critical areas on the wind turbine structure are known at this time, the measured loads should be combined prior to the load cycle counting to yield stress-values at the critical points. Combination of load-values from the load-amplitude spectra can only be done in an approximate manner.

If the wind speeds are recorded at the hub height +- the rotor radius they can be combined to give the vertical wind gradient as defined in Section 5.2.1.

6.2.2 Load signal analysis

All time series recordings should be summarised in terms of the basic statistics: mean value, standard deviation, minimum and maximum value, of the measured and/or combined signals.

It is suggested that the fundamental load time series from the production operation recordings are further analysed with the purpose of separating periodic and stochastic load components and obtaining information on the wind turbine dynamics. The following is recommended:

- <u>Azimuthal averaging.</u> The load time series are averaged against the azimuthal rotor position using the method of bins in order to obtain the average cyclic behaviour. The bin width should not exceed 18 degrees.
- <u>Spectral analysis.</u> Power spectra are calculated for the load time series in order to identify structural resonances and narrow banded excitation.

6.2.3 Load cycle counting

It is recommended that fatigue life evaluation be based on a variable-amplitude load representation in terms of load-cycle occurrence, cycle ranges and cycle means. It is furthermore recommended that the load-cycles are identified and counted using the "Rainflow" algorithm, appendix A and ref. 8-9.

The load-history peak/trough values are converted into no less than 50 integer levels. Each level corresponds to a load level S_i. The result of the rainflow counting procedure shall be given as either 1) a from-to Markov matrix A, in which the element a_{ij} gives the number of counted load variations from level j to level i, or 2) a range-mean matrix M, in which the element m_{rm} gives the number of counted ranges with size r and mean m where $r=S_i-S_j$ and $m=(S_i+S_j)/2$.

Knowing the relation between the measured loads and the stress levels at the critical locations and knowing the allowable number of stress cycles as function of stress level (e.g. S-N curves, Goodman diagrams) fatigue damage can be estimated using the Palmgren-Miner linear damage rule. The procedure is described in appendix C.

6.3 Correction for site characteristics

When the results of the analysed fatigue load measurements are applied to predict the fatigue life of a wind turbine of the same type but located at a site with different wind characteristics, corrections for the site effects should be made. Of primary importance are

1) The annual wind speed distribution.
2) Fluctuations in the aerodynamic load from wind turbulence and the vertical wind speed gradient.

It is recommended that adjustments of the number of occurrences and/or the time spent per year in each mode of operation corresponding to starting, stopping and production, are made proportional to changes in the frequency of the relevant wind speed ranges.

The fluctuating part of the aerodynamic loads during a production operation mode can, for a homogeneous site, be assumed linearly dependent on the turbulence intensity. It is recommended that the load amplitudes, excluding the in-plane blade bending moment, are adjusted according to a change in average turbulence intensity for the site. If the data contains time series recordings during production operation with turbulence intensities varying over the range of interest, a mean load amplitude factor can be calculated from the measurements. Otherwise proportionality can be assumed, however, no reduction of the load amplitudes should be made in this case.

7. CONTENT OF TEST REPORT

The test report should include, but not be limited to, the items listed below:

1. Description of the wind turbine, including a sketch or a photograph. The rotor speed and the fundamental resonance frequencies of the wind turbine (blade, drive train, tower) should be given.
2. Site lay-out including a sketch or a photograph.
3. Terrain specification of the test site region, see Section 4.2.
4. Description of the instrumentation including type and location. If calibration is applicable, the method of calibration and the time interval must also be described.
5. Description of the data acquistion system.
6. The duty cycle recorded at the test site. As a minimum the results of the analysis in section 6.1 should be reported.
7. Time series recordings. The report should contain:

   i) A table giving the basic statistics (mean value, standard deviation, minimum and maximum value) of the measured and/or the combined signals for all time series recordings.

   ii) Typical time history plots for each mode of operation of the measured resulting signals.

   iii) If possible, averaged cyclic behavior and power spectra of load signals for production operation modes.
8. Load cycle counts. The following results of the rainflow counting should be reported:

   i) Rain flow counting matrices for all recorded time series.

   ii) Graphs showing the rainflow load histogram (load range as a function of number of occurences for each load type and each mode of operation).

   iii) Graphs showing the total load spectrum based on the measured duty cycle and one year of operation for each load type.
9. Site correction. If possible, load amplitude corrections as function of average turbulence intensity should be reported, see Section 6.3.

8. REFERENCES

1. Recommended Practices for Wind Turbine Testing and Evaluation: 1. Power Performace Testing. 1. Edition 1982. Submitted to the Executive Committee of the International Energy Agency Programme for Reasearch and Development on Wind Energy Conversion Systems.

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APPENDIX A. Description of the Rainflow Counting Method

In this appendix a short description is given of the two-dimensional counting method known as the "Rainflow" method. Other counting methods exist, but "Rainflow Counting" is the most generally accepted as it properly accounts for the hystereses effects. Thus one full cycle is counted for each closed stress-strain hysteresis path, and half cycles are added for succeeding maxima and minima in the local stress which do not represent closed cycles. The description is functional and is intended for an easy computer implementation of the method. A more complete description is found in references [8] and [9].

A1. Conversion of a load-time history into a peak/through sequence

A load history x (t) (0 to T) may be either recorded in an analog format and converted into a digital form or recorded directly in a digital format as a series of integer values x_j.

The values x_j are integers from 0 to k.

This sequence is searched for peak/through values. The successive extremes found are called S_p (p=1 to n). A range filter of size R is very often used to remove jitters. This means that successive peaks and troughs must differ by a least a value R if they are to be included as valid extreme values. The algorithm is defined in the flow diagram shown in figure A1.

A2. Description of the cycle counting procedure

The cycle counting procedure consists of two phases. In the first phase, the peak/trough sequence is searched for range-pairs. Range-pairs are illustrated in figure A2. Rather than splitting up the load trace shown in three successive ranges, the load trace is interpreted as one "main" load variation or range with superimposed on it a small load cycle or range pair.

At the end of this phase there remains a "residu" which is analyzed by counting the successive ranges separately.

The counting results will be stored in a Markov-Matrix A of size (k+1) x (k+1), in which element a_{ij} is the number of counted ranges "from" level j "to" level i. Obviously, the elements for which $i<j$ (elements above the main diagonal) contain downward load changes, and vice versa.

Phase I: Starting with the first recorded peaks/troughs, groups of four successive extremes S_{p-3}, S_{p-2}, S_{p-1} and S_p are considered.

In this group a range-pair is counted if the value of the two "inner" extremes S_{p-2} and S_{p-1} fall within the range bound by S_p and S_{p-3}: (See Fig. A3).

Counting a pair implies that the value of the appropriate element a_{ij} in the 'upper triangle" and the opposite element a_{ji} in the lower triangle of the Markov-Matrix are increased by one.

Next, the "counted" extremes S_{p-2} and S_{p-1} are deleted from the record and the procedure is repeated "moving backward", by considering the four extremes S_{p-5}, S_{p-4}, S_{p-3} and S_p.

If the counting criterion is not met, one moves one step forward, hence the extremes S_{p-2}, S_{p-1}, and S_{p+1} are considered and so on.

It can be easily shown that if the whole sequence has been searched for pairs in this way, eventually a "residu" remains which has the shape indicated in figure A4, namely a "diverging" part followed by a converging part.

Phase II: The "residu" S_1, S_2, S_3 etc. is simply counted as successive single ranges S_1-S_2, S_2-S_3, etc.

It can easily be shown that the maximum length of the residu is 2k+1 extremes, containing 2k ranges.

A complete algorithm for the "rainflow" counting method is given in figure A5.

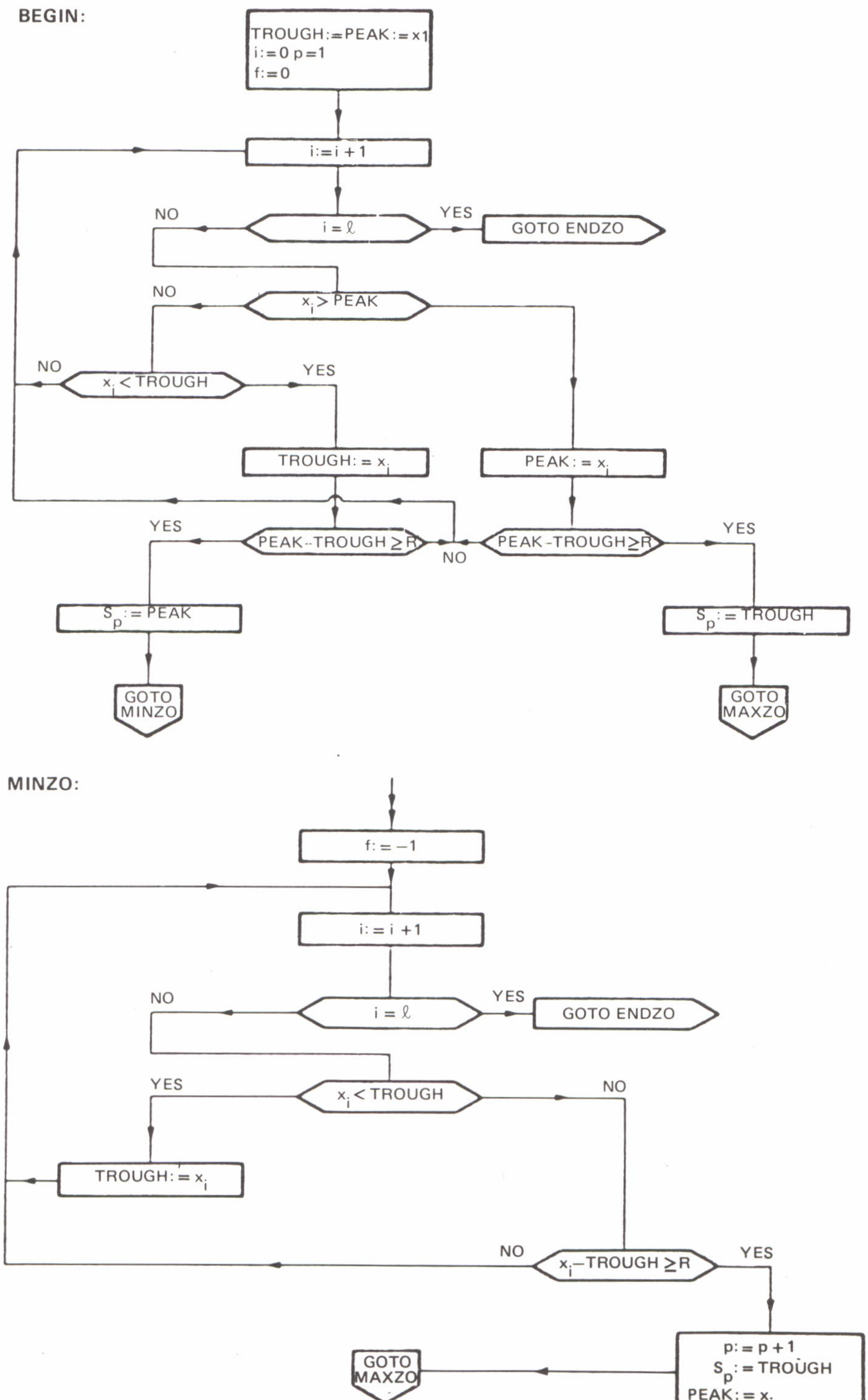
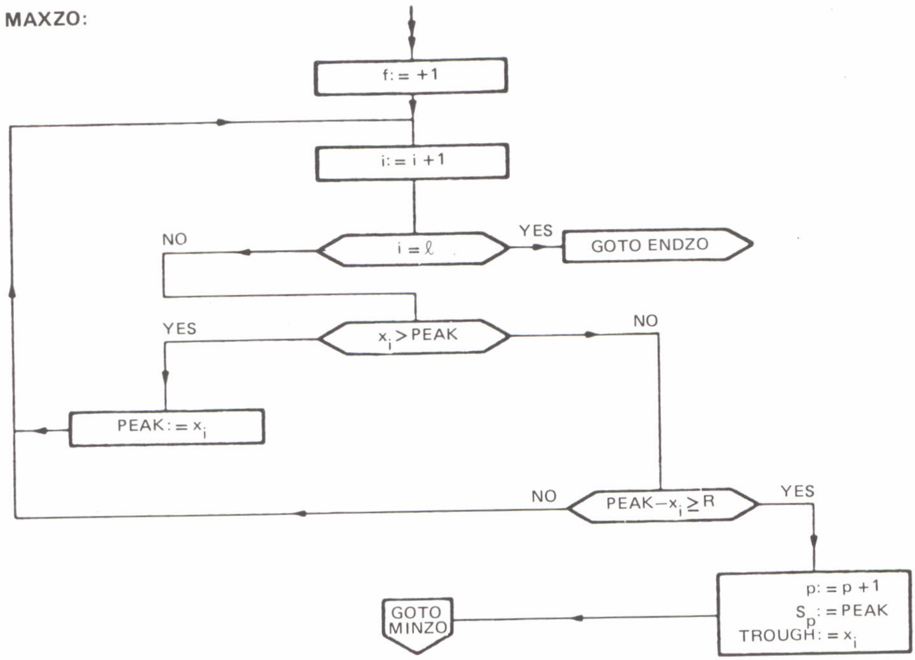


Fig. A1. Peak/trough search algorithm.



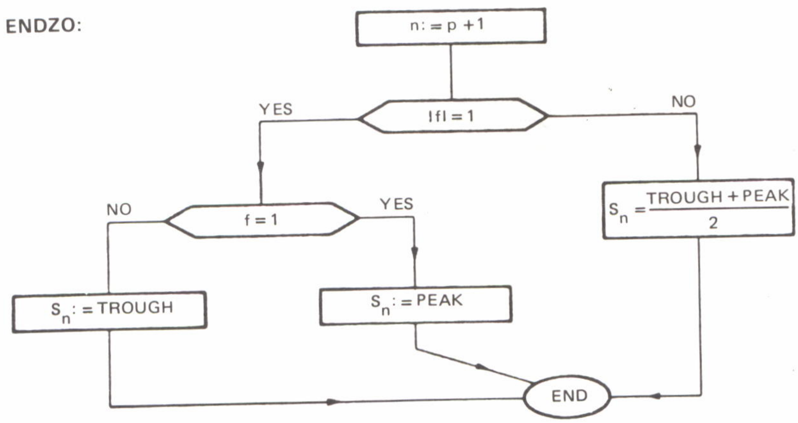


Fig. A1. (cont.). Peak/trough search algorithm.

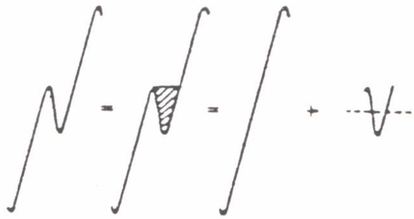
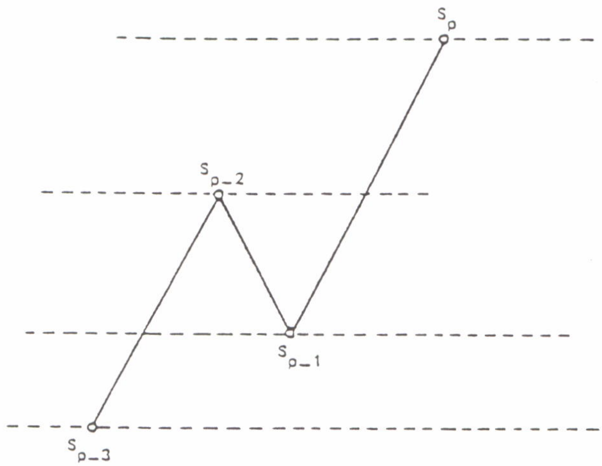


Fig. A2. Range pair counting principle.



THE RANGE PAIR S_{p-2}–S_{p-1} AND S_{p-1}–S_{p-2} IS COUNTED <u>IF</u>

$S_{p-2>p-3}$ AND $S_{p-1} \geq S_{p-3}$ AND $S_p \geq S_{p-2}$
OR
$S_{p-2} < S_{p-1}$ AND $S_{p-1} \leq S_{p-3}$ AND $S_p \leq S_{p-2}$

Fig. A3. Range pair counting criterion.

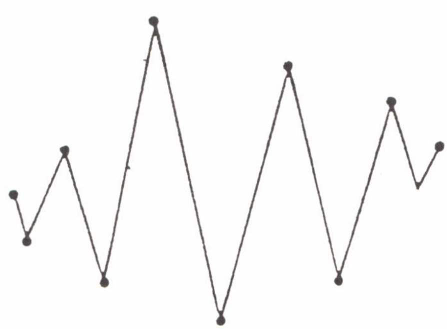


Fig. A4. Shape of the residu after counting phase I.

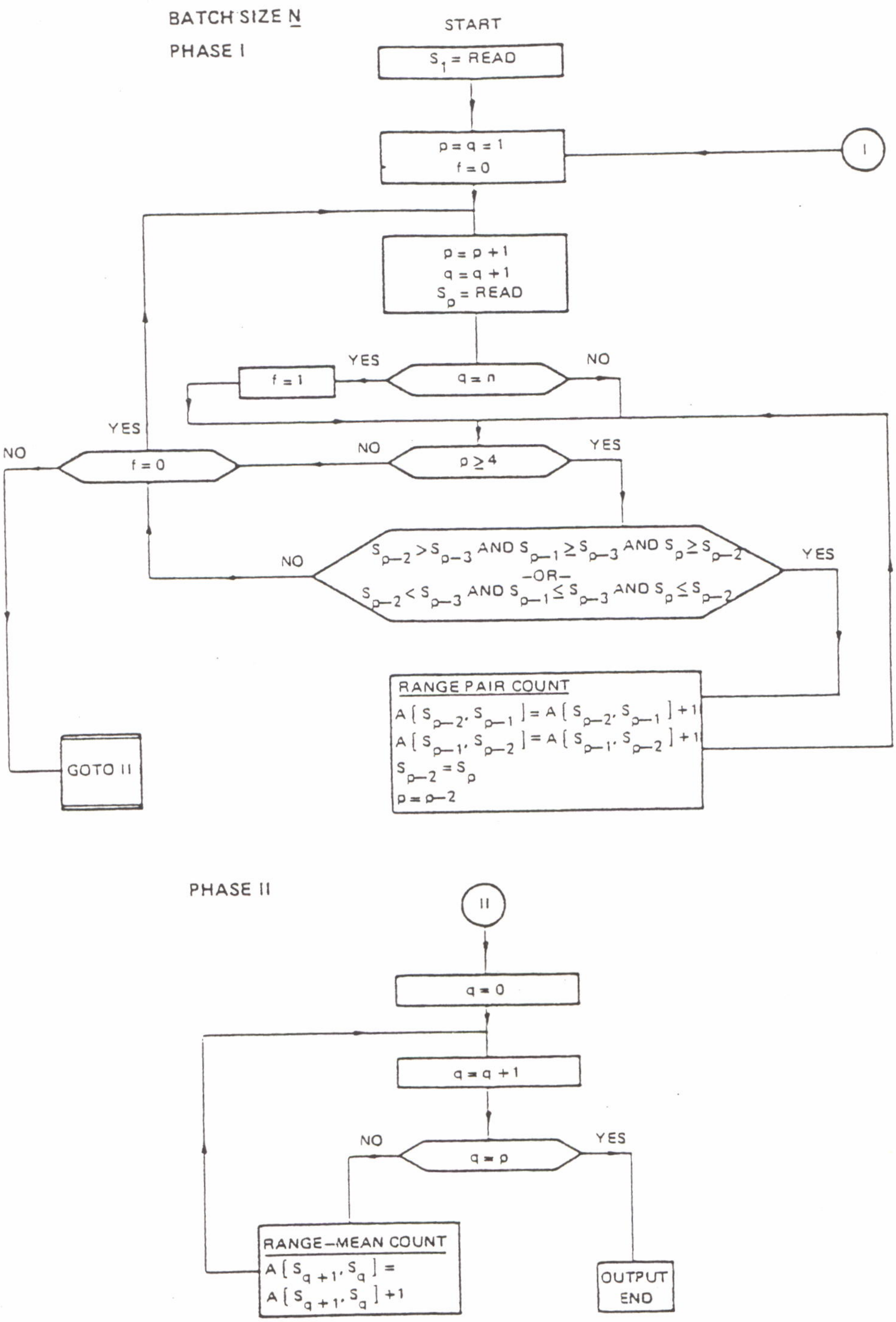


Fig. A5. "Rainflow" algorithm.

APPENDIX B. Combination of Load Spectra

The stresses at a fatigue critical location of the wind turbine structure may be caused by a combination of the fundamental loads which has been measured and analysed according to this document. During fatigue damage accumulation the stresses in the load carrying structure are in general sufficiently low that linear elastic material behaviour can be assumed. The stress can then be expressed as

$$\sigma = \sum_i \gamma_i S_i \qquad \text{(B1)}$$

where S_i are the fundamental loads. The factors γ_i can be determined with finite-element analysis or from e.g. beam theory. In the latter case γ_i may consist of a section modulus times a stress concentration factor.

Since the rainflow counting is a highly nonlinear process, a rainflow matrix of the stress cycles of σ_i can not be calculated from rainflow matrices of S_i in a exact sense when more than one fundamental load contributes. In such cases it is strongly recommended to calculate the stress signal directly from the recorded time series prior to the cycle counting. The rainflow matrix can then be determined using the counting algorithm on the synthetic stress time series.

If the recommended procedure is not possible, a rainflow matrix of the stress must be estimated from the rainflow matrices of the fundamental loads, using a number of conservative assumptions. These are

- load peaks occur simulataneously for all fundamental loads that contribute to the stress
- high-amplitude cycles should be combined with high-amplitude cycles
- The mean values should be combined in the most unfavourable manner to produce the largest mean stress value

The procedure is illustrated below using the averaged load spectra of two fundamental loads and disregarding the mean values. The load spectra are illustrated in fig. B1 a) and b). The synthetic stress cycle spectrum (number of exceedances versus cycle amplitude) is then generated as follows

n_1 cycles with the amplitude $\sigma_1 = \gamma_1 S_1^1 + \gamma_2 S_2^1$

n_2 cycles with the amplitude $\sigma_2 = \gamma_1 S_1^2 + \gamma_2 S_2^1$

$m_1 - n_1 - n_2$ cycles with the amplitude $\sigma_3 = \gamma_1 S_1^3 + \gamma_2 S_2^1$

m_2 cycles with the amplitude $\sigma_4 = \gamma_1 S_1^3 + \gamma_2 S_2^2$

m_3 cycles with the amplitude $\sigma_5 = \gamma_1 S_1^3 + \gamma_2 S_2^3$

$n_1 + n_2 + n_3 - m_1 - m_2 - m_3$ cycles with the amplitude $\sigma_6 = \gamma_1 S_1^3$

n_4 cycles with the amplitude $\sigma_7 = \gamma_1 S_1^4$

The resulting stress spectrum is shown in fig. B1 c)

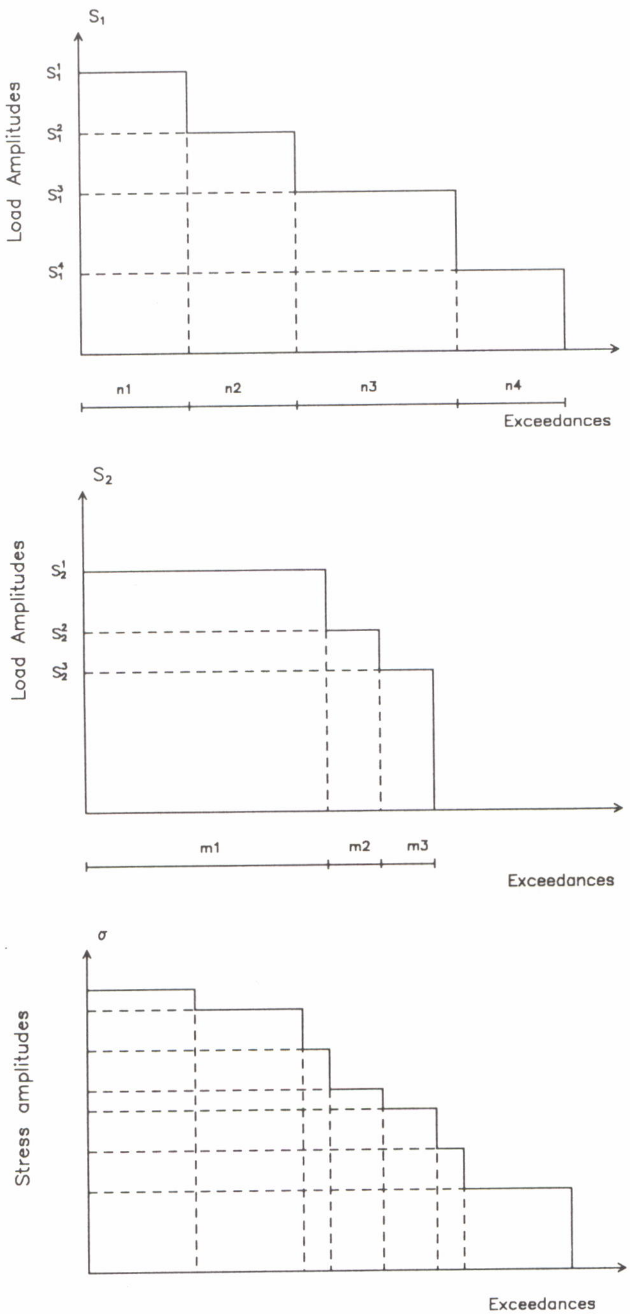


Fig. B1. Combination of load spectra.

APPENDIX C. Fatigue Damage Calculations

The estimation of fatigue damage accumulation given a complex variable amplitude cyclic loading in terms of a Rain flow from- to or range-mean matrix or simply a load spectrum must usually be carried out according to a National or International Code of Practice. Coefficients of safety may be applied in a variety of ways, and this appendix cannot give even a brief account of the various approaches. Basic for all approaches is a damage accumulation rule, and we shall here briefly describe the most widely used, the so-called Palmgren-Miner linear damage rule. For methods to obtain an acceptable degree of conservatism or safety the user of the document is referred to the relevant code of practice.

The basic assumption of the Palmgren-Miner rule is that cumulative damage during cyclic loading is related to the work absorbed by the component in question. The ratio of the number of applied stress cycles with a given range and mean level to the number of cycles to failure constitutes the expended part of the useful fatigue life. The allowable number of cycles N_i with the range r_i and the mean m_i is given by standard fatigue curves, e.g. S-N curves as illustrated in figure C1 or Goodman diagrams. The fatigue damage due to n_i cycles with the same mean and range is then specified as

$$d_i = \frac{n_i}{N_i} \qquad \text{(C1)}$$

The analysis can then be repeated for all stress cycles and the corresponding means of the expected lifetime stress history. The fatigue life consumption is determined from

$$\Sigma \frac{n_i}{N_i} \qquad \text{(C2)}$$

The fatigue design is adequate if

$$d \leq 1 \qquad \text{(C3)}$$

A calculation of the fatigue lifetime will be based on the recorded duty cycle and the measured and reduced data from the time series recordings together with the relevant material fatigue curves. In addition extreme load cases with theoretically calculated cycle ranges and means as well as number of cycles should be included.

We shall assume that the wind speed distribution from the duty cycle recordings is representative for the site, and that the turbulence intensities during the time series recordings are not significantly smaller than the average duty cycle turbulence intensity. In this case the number of load case occurrences and the calculated rainflow matrices are used as follows

- Calculate the fatigue damage using (C2) for each load case. Note that production operation results in several load cases corresponding to each wind speed bin, each with a number of occurrence n_i and a fatigue damage d_i.

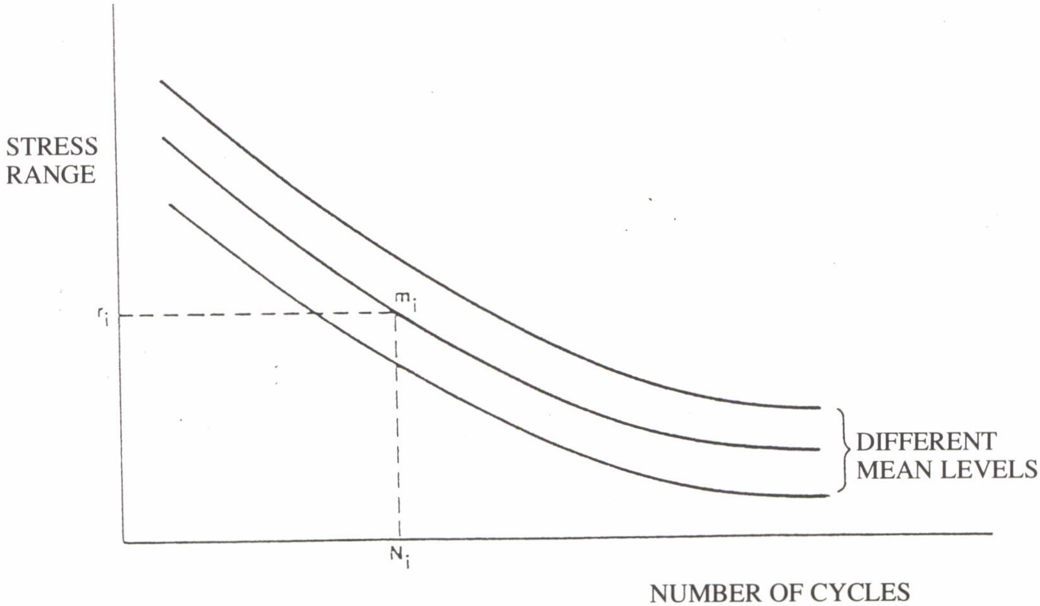


Fig. C1. S-N curves

- Calculate the accumulated fatigue damage for one year using the number of occurrence from the duty cycle recordings n_i and the calculated fatigue damages

  $D = \Sigma\ n_i\ d_i$

  $+n_{stop}\ d_{stop} + n_{start}\ d_{start}$; low wind speed

  $+n_{stop}\ d_{stop} + n_{start}\ d_{start}$; high wind speed

  $+n_{still}\ d_{still}$

  $+ \Sigma\ n_{abnormal}\ d_{abnormal}$

  $(+ \Sigma\ n_{extreme}\ d_{extreme})$ (C4)

- Estimate the fatigue life time T in years for the material at the location in question from

  $T = 1/D$ (C5)

For a site with wind conditions which differs from conditions during the duty cycle measurements, the number of occurrences and cycle amplitudes should be modified to reflect the actual conditions, see Section 6.3.

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