TECHNICAL SPECIFICATION

IEC TS 61400-13

First edition
2001-06

Wind turbine generator systems –

Part 13:
Measurement of mechanical loads

Aérogénérateurs –

Partie 13: Mesure des charges mécaniques

Reference number
IEC/TS 61400-13:2001(E)

Publication numbering

As from 1 January 1997 all IEC publications are issued with a designation in the 60000 series. For example, IEC 34-1 is now referred to as IEC 60034-1.

Consolidated editions

The IEC is now publishing consolidated versions of its publications. For example, edition numbers 1.0, 1.1 and 1.2 refer, respectively, to the base publication, the base publication incorporating amendment 1 and the base publication incorporating amendments 1 and 2.

Further information on IEC publications

The technical content of IEC publications is kept under constant review by the IEC, thus ensuring that the content reflects current technology. Information relating to this publication, including its validity, is available in the IEC Catalogue of publications (see below) in addition to new editions, amendments and corrigenda. Information on the subjects under consideration and work in progress undertaken by the technical committee which has prepared this publication, as well as the list of publications issued, is also available from the following:

- **IEC Web Site (www.iec.ch)**

- **Catalogue of IEC publications**

  The on-line catalogue on the IEC web site (www.iec.ch/catlg-e.htm) enables you to search by a variety of criteria including text searches, technical committees and date of publication. On-line information is also available on recently issued publications, withdrawn and replaced publications, as well as corrigenda.

- **IEC Just Published**

  This summary of recently issued publications (www.iec.ch/JP.htm) is also available by email. Please contact the Customer Service Centre (see below) for further information.

- **Customer Service Centre**

  If you have any questions regarding this publication or need further assistance, please contact the Customer Service Centre:

  Email: custserv@iec.ch
  Tel: +41 22 919 02 11
  Fax: +41 22 919 03 00

TECHNICAL SPECIFICATION

IEC TS 61400-13

First edition
2001-06

Wind turbine generator systems –

Part 13: Measurement of mechanical loads

Aérogénérateurs –

Partie 13: Mesure des charges mécaniques

International Electrotechnical Commission 3, rue de Varembé Geneva, Switzerland
Telefax: +41 22 919 0300 e-mail: inmail@iec.ch IEC web site http://www.iec.ch

Commission Electrotechnique Internationale
International Electrotechnical Commission
Международная Электротехническая Комиссия

PRICE CODE XB

For price, see current catalogue

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND TURBINE GENERATOR SYSTEMS –

Part 13: Measurement of mechanical loads

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of the IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested National Committees.
3) The documents produced have the form of recommendations for international use and are published in the form of standards, technical specifications, technical reports or guides and they are accepted by the National Committees in that sense.
4) In order to promote international unification, IEC National Committees undertake to apply IEC International Standards transparently to the maximum extent possible in their national and regional standards. Any divergence between the IEC Standard and the corresponding national or regional standard shall be clearly indicated in the latter.
5) The IEC provides no marking procedure to indicate its approval and cannot be rendered responsible for any equipment declared to be in conformity with one of its standards.
6) Attention is drawn to the possibility that some of the elements of this technical specification may be the subject of patent rights. The IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. In exceptional circumstances, a technical committee may propose the publication of a technical specification when

- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC 61400-13, which is a technical specification, has been prepared by IEC technical committee 88: Wind turbine systems.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
88/120/CDV	88/132/RVC

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 3.

The committee has decided that the contents of this publication will remain unchanged until 2004. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

A bilingual version of this technical specification may be issued at a later date.

INTRODUCTION

In the process of structural design of a wind turbine, thorough understanding about, and accurate quantification of, the loading is of utmost importance.

In the design stage, loads can be predicted with aeroelastic models and codes. However, such models have their shortcomings and uncertainties, and they always need to be validated by measurement. Furthermore, measurements can be used for the direct determination of structural loads in specific conditions.

Mechanical load measurements can be used both as the basis for design and as the basis for certification. Design aspects for wind turbines are covered by IEC 61400-1 whilst certification procedures are described in IEC WT 01*. This technical specification is aimed at the test engineer who will design and implement the test programme to meet the specific design or certification needs. The specification provides specific guidance on load measurements on key structural components and load paths. Data analysis procedures are also outlined. The specification describes how to collect various types of time-series or statistical load information. Two types of situation are considered – steady-state operation and transient operation. The prescribed measurement load cases mirror the design load cases within IEC 61400-1, the wind turbine safety standard.

* IEC WT 01:2001, IEC System for Conformity Testing and Certification of Wind Turbines – Rules and procedures

WIND TURBINE GENERATOR SYSTEMS –

Part 13: Measurement of mechanical loads

1 General

1.1 Scope and object

This part of IEC 61400 deals with mechanical load measurements on wind turbines. It mainly focuses on large (>40 m^2) electricity generating horizontal axis wind turbines. However, the methods described might be applicable to other wind turbines as well (for example, mechanical water pumpers, vertical axis turbines).

The object of this specification is to describe the methodology and corresponding techniques for the experimental determination of the mechanical loading on wind turbines. This technical specification is intended to act as a guide for carrying out measurements used for verification of codes and/or for direct determination of the structural loading. This specification is not only intended as one coherent measurement specification but can also be used for more limited measurement campaigns.

1.2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of IEC 61400. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of IEC 61400 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60050(415):1999, *International Electrotechnical Vocabulary (IEV) – Part 415: Wind turbine generator systems*

IEC 61400-1:1999, *Wind turbine generator systems – Part 1: Safety requirements*

IEC 61400-12:1998, *Wind turbine generator systems – Part 12: Wind turbine power performance testing*

ISO 1995, *Guide to the expression of uncertainty in measurement*

ISO 2394:1998, *General principles on reliability for structures*

1.3 Definitions

For the purpose of this technical specification, the definitions related to wind turbine systems or wind energy in general of IEC 60050(415) and the following definitions apply.

1.3.1
blade
rotating aerodynamically active part of the rotor

1.3.2
blade root
that part of the rotor blade that is connected to the hub of the rotor

1.3.3
calibration load
forces and moments applied during calibration

1.3.4
capture matrix
organization of the measured time series according to mean wind speeds and turbulence intensities

1.3.5
chord
length of a reference straight line (the chord line) that joins, by certain defined conventions, the leading and trailing edges of a blade airfoil cross-section

1.3.6
chord line
reference straight line that joins, by certain defined conventions, the leading and trailing edges of a blade airfoil cross-section

1.3.7
design loads
loads that the turbine is designed to withstand. They are obtained by applying the appropriate partial load factors to the characteristic values

1.3.8
flap
direction which is perpendicular to the swept surface of the undeformed rotor blade axis

1.3.9
hub
fixture for attaching the blades or blade assembly to the rotor shaft

1.3.10
lead-lag
direction which is parallel to the plane of the swept surface and perpendicular to the longitudinal axis of the undeformed rotor blade

1.3.11
nacelle
housing which contains the drive train and other equipment on the top of a HAWT tower

1.3.12
natural frequency (eigenfrequency)
frequency at which a structure will choose to vibrate when perturbed and allowed to vibrate freely

1.3.13
outboard
towards the blade tip

1.3.14
partial safety factors
factors that are applied to loads and material strengths to account for uncertainties in the representative (characteristic) values

1.3.15
radial position
distance from the rotor centre in a plane perpendicular to the rotor axis

1.3.16
rotor centre
point on the main shaft in the plane perpendicular to the main shaft that contains the blade co-ordinate origin of the reference blade

1.3.17
rotor plane
plane perpendicular to the main shaft and which includes the rotor centre

1.3.18
spanwise
direction parallel to the longitudinal axis of a rotor blade

1.3.19
steady-state operation
state of operation of the turbine during which it remains in a steady state such as during power production, power production + fault condition and when parked or idling and for which the external conditions also remain essentially steady or characterized by stationary random processes for the duration of the measurement

1.3.20
transient event
event during which the state of operation of the wind turbine changes, such as during shut-down

1.3.21
test load
forces and moments applied during a test

1.3.22
turbulence intensity
turbulence intensity is the ratio of the standard deviation of the wind speed in a given time interval to the mean wind speed in the same time interval

1.3.23
yaw position
angle between the vertical projection of the centre line of the main shaft on the tower base and the X-axis of the tower co-ordinate system (which is to be defined as appropriate according to the site and the shape of the tower cross-section). The yaw position is positive rotating counter-clockwise (top view)

1.4 Symbols, units and abbreviations

1.4.1 Symbols and units

ε	strain	–
φ_F	angle for yaw misalignment	[°]
B	number of blades	–
f	frequency	[Hz]
F	forces	[N]
I	turbulence intensity	–
I	index for wind speed bin	–
j	index for accumulated number of alternating load cycles	–
k	index for specific load	–
M_{be}	blade-root lead-lag bending moment	[Nm]
M_{bf}	blade-root flap-bending moment	[Nm]
M_{eq}	equivalent load	[Nm, N]

M_{tm}	tower base normal bending moment	[Nm]
M_{tl}	tower base lateral bending moment	[Nm]
M_{tilt}	rotor tilt moment	[Nm]
M_{ttm}	tower top normal moment	[Nm]
M_{ttl}	tower top lateral moment	[Nm]
M_{ttt}	tower top torsion moment	[Nm]
m	slope of S-N curve	–
n	number of measurements/results	–
N	number of cycles to failure	–
R	rotor radius	[m]
$R^{e}{}_{ijk}$	extrapolated load range	[Nm, N]
$R^{m}{}_{ijk}$	measured load range	[Nm, N]
S	load amplitude	[Nm, N]
s_I	type A standard uncertainty	–
T_{rotor}	rotor torque	[Nm]
u	measured value for uncertainty assessment	–
u_I	type B standard uncertainty	–
x_b, y_b, z_b	blade co-ordinates (see figure A.1)	–
x_h, y_h, z_h	hub co-ordinates (see figure A.2)	–
x_I	input quantity	–
x_n, y_n, z_n	nacelle co-ordinates (see figure A.3)	–
x_t, y_t, z_t	tower co-ordinates (see figure A.4)	–
y	quantity to be measured	–
v_{e1}	extreme wind speed with return period of one year	[m/s]
v_{hub}	wind speed at hub height	[m/s]
v_{in}	cut-in wind speed	[m/s]
v_r	rated wind speed	[m/s]
v_{out}	cut-out wind speed	[m/s]

1.4.2 Abbreviations

MLC	measurement load case
DLC	design load case
SO	steady-state operation
TE	transient event
TI	turbulence intensity

2 Safety during testing

Certain measurement load cases involve deliberate operation of the turbine in extreme and/or emergency fault conditions (for example, grid loss). As the purpose of the tests and measurements in most cases is to verify loads on a prototype turbine, it shall not be assumed that the turbine will behave and respond as intended. Therefore, such tests shall always be assumed to be dangerous and due regard shall be taken for personnel safety. On this basis, such tests shall be initiated and observed from a safe position, usually at a certain distance upwind the rotor plane and they shall not be carried out with personnel inside or on the nacelle or tower or within the rotor plane. All tests and test procedures shall be agreed with the turbine manufacturer before implementation to ensure that the turbine integrity, and hence that personnel safety, is not compromised. Requirements from existing applicable safety standards shall be followed.

3 Load measurement programmes

3.1 General

The measurement programme involves collecting both a comprehensive statistical database and a set of time series, which define the behaviour of the turbine in certain specific situations. In this clause, a system of measurement load cases (MLCs) is defined to determine the wind turbine loads in conditions corresponding to a selection of design load cases (DLCs) of IEC 61400-1. The MLCs may directly be used for documentation of the load in relation to the DLCs, or the MLCs may provide a basis for the validation of calculation models at specific and well-defined external conditions. Subsequently, the models can be used to estimate the loads at the design conditions. This clause also provides specifications for the quantities to be measured.

3.2 Measurement load cases (MLCs)

3.2.1 General

This subclause describes how to build up load measurement campaigns from a number of well-defined MLCs. The MLCs are defined in relation to the DLCs, described in IEC 61400-1. Hence, not all DLCs can be reasonably verified by measurement.

The MLCs define the main external conditions and the operational conditions of the turbine during the measurement campaigns. The external conditions include meteorological parameters such as wind speed, turbulence intensity and air density. The operational conditions include operational parameters such as rotational speed, yaw error, electrical power and blade pitch angle. The operational conditions depend on the wind turbine configuration and shall be specified for each particular case.

Due to the stochastic character of the external conditions, measurements of each MLC have to be repeated several times in order to reduce the statistical uncertainty. The minimum number of measurements at each MLC is specified in this subclause.

Some of the DLCs of IEC 61400-1 and covered by MLCs defined in this specification are specified at external conditions that are difficult to achieve during a measurement campaign. In particular, the high wind speeds for those DLCs are difficult to obtain during the measurement campaign or at a specific site. For example, it is not possible to forcefully apply the extreme coherent gust to the turbine. In such cases, these load cases shall be assessed at wind speeds which are as high as possible.

The measured time histories are classified in two ways: one considering steady-state operation (SO) and one considering transient events (TE). In this way, all measurements can be classified in measurement load cases which relate to the IEC 61400-1 DLCs.

Tables 1 and 2 show the MLCs that are recommended to be recorded. The MLCs defined in the tables may not be complete. Additional MLCs may be necessary depending on the wind turbine concept and control and safety strategy.

3.2.2 MLCs during steady-state operation

Power production

During power production, measurements shall be performed in the wind speed range from cut-in to cut-out and in a range of turbulence intensity levels described in the following subclause.

Power production with occurrence of fault

According to IEC 61400-1 any fault in the control or protection systems, or any internal fault in the electrical systems being significant for the wind turbine loading, shall be considered to occur during power production. The occurrence of a fault in the control system, which is considered as a normal event, shall be analysed. A typical fault condition could be the operation at extreme yaw misalignment due to a faulty wind vane, which might not be relevant for a free yaw wind turbine. Faults in the protection system or in the internal electrical system, not causing an immediate shut-down of the wind turbine and consequently leading to higher fatigue loading, shall be considered. An example could be operation with one tip brake activated. The possible fault conditions shall be considered for each wind turbine and application in order to define the measurement campaigns.

Parked, idling

The loads on the parked wind turbine, which may be either in a standstill or idling condition, shall be measured. It is recommended that measurements be performed at wind speeds as high as possible.

Table 1 – MLCs during steady-state operation related to the DLCs defined in IEC 61400-1

MLC number	Measurement load case MLC	DLC number (IEC 61400-1)	Wind condition at DLC	Remarks
1.1	Power production	1.2	$v_{in} < v_{hub} < v_{out}$*	In this mode of operation, the wind turbine is running and connected to the grid
1.2	Power production plus occurrence of fault	2.3	$v_{in} < v_{hub} < v_{out}$*	Any fault in the control or protection system, which does not cause an immediate shut-down of the turbine
1.3	Parked, idling	6.2	$v_{in} < v_{hub} < 0,75\ v_{e1}$*	When the wind turbine is parked, the rotor may either be stopped or idling

* Has to be divided further into wind speed bins and turbulence bins.

3.2.3 MLCs during transient events

Start-up

This design situation includes all events resulting in loads on the wind turbine during the transients from standstill or idling to power production. The normal start-up of the turbine shall be performed slightly below cut-out wind speed and at cut-in wind speed. If the turbine operates at more than one fixed speed, cut-in on the different rotational speeds shall be evaluated too.

Normal shut-down

This design situation includes all events resulting in loads on a wind turbine during the normal transient caused by going from a power production situation to a standstill or idling condition. The normal shut-down is recommended to be performed at cut-in wind speed, at rated power and at cut-out wind speed.

Emergency shut-down

The loads arising from emergency shut-down shall be considered. It is recommended to perform the emergency shut-down near cut-in wind speed and above rated wind speed.

Grid failure

The loads arising from grid failure shall be considered. It is recommended to perform the simulation of grid disconnection above rated wind speed and near cut-out wind speed.

Overspeed activation of the protection system

The loads during activation of the protection system due to turbine overspeed shall be measured. All combinations of braking procedures and activation methods shall be considered. It is recommended to perform this test above rated wind speed.

Table 2 – Measurement of transient load cases related to the DLCs defined in IEC 61400-1

MLC	Measurement load case MLC	DLC	Target wind speed
2.1	Start-up	3.1	v_{in} and > v_r + 2 m/s
2.2.	Normal shut-down	4.1	v_{in}, v_r and > v_r + 2 m/s
2.3	Emergency shut-down	5.1	v_{in} and > v_r + 2 m/s
2.4	Grid failure	1.5	v_r and > v_r + 2 m/s
2.5	Overspeed activation of the protection system	5.1	> v_r + 2 m/s

Ideally the measurements should be taken at v_{out}. As this is impractical, the measurements are taken at wind speeds higher than v_r + 2 m/s.

3.2.4 Capture matrix

The capture matrix is used to organize the measured time series. The capture matrix has two objectives: it can be used as a guideline for programming the data acquisition system for automatic and unattended operation and it can be used as a tool to decide when the measurement requirements are fulfilled.

For steady-state operation, the operational condition is defined and the mean wind speed and turbulence intensity are calculated. If it is decided to store the time series, the relevant matrix element is updated. Consequently, it is simple to decide when the recommended number of time series is reached. For a transient event the actual wind speed is written in the capture matrix.

The bin sizes of the matrix and the number of data sets in each matrix element have to be adapted for each specific measurement campaign. If the relevant status parameters from the control system are recorded, capturing the measurements during some of the transient events can be recorded automatically too. The scheme of the complete capture matrix is given in table 3.

If the measurement site terrain characteristics differ significantly in the various wind direction sectors, the capture matrix can additionally be divided into pre-selected wind directions sectors. The overall requirements on the database remain the same.

Power production

During the measurement campaign the data should be classified according to the wind speed and turbulence intensity. Even though there is no requirement on the turbulence intensity at high wind speeds, the recorded data shall be classified according to the turbulence bins.

It is recommended that the wind speed be divided into bin intervals of 1 m/s and the turbulence intensity into 2 % bin intervals. The accumulated number of 10-min time series at each wind speed bin up to v_r shall be at least 30. This corresponds to 5 h of raw data in total at each wind speed bin from v_{in} to v_r. In addition to the totally required amount of data, the measurements shall be recorded at different turbulence intensities. As a minimum four turbulence bins at each wind speed bin should include at least three time series.

In the wind speed range from v_r to v_{out} minus 5 m/s the accumulated number of 10-min time series at each wind speed bin shall be at least eight. No further conditions are put on the turbulence intensity in the same range of v_r to v_{out} minus 5 m/s. In the wind speed bin from v_{out} minus 5 m/s up to v_{out}, the duration of the time series to be recorded may be reduced to 2 min. At least three time series at each wind speed bin from v_{out} minus 5 m/s to v_{out} minus 1 m/s should be recorded. At least one time series shall be recorded at v_{out}. No conditions are put on the turbulence intensity in the range from v_{out} minus 5 m/s to v_{out}. The 2-min time series may be derived from the 10-min time series, on condition that there is no overlap in the resulting 2-min series.

Power production and occurrence of fault

The wind speed is divided into three intervals, from v_r minus 6 m/s to v_r minus 2 m/s, from v_r minus 2 m/s to v_r plus 2 m/s, and for wind speeds larger than v_r plus 2 m/s. The duration of each time series shall be more than 2 min. The relevant fault conditions shall be evaluated for each particular case.

Parked (standstill or idling)

The wind speed bin size for standstill or idling MLCs is recommended to be 4 m/s. The duration of the time series is recommended to be 10 min. Measurements at parked conditions should be made at a variety of yaw misalignment angles, including the most unfavourable inflow angles.

Table 3 – Capture matrix for normal power production

Normal power production Wind speed bin size: 1 m/s Turbulence bin size: 2 %														
Time series length	**10 min**										**At least 2 min**			
Wind (m/s) ⇒ I (%) ⇓	v_{in} -	…	4,5 5,5	…	…	v_r	…		…	…	v_m	…	…	v_{out}
<3														
3-5														
5-7														
7-9														
…														
…														
27-29														
>29														
Minimum number of turbulence bins with at least three time series	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**–**	**–**	**–**	**–**	**–**	**–**
Minimum recommended number of time series for empirical load determination	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**8**	**8**	**8**	**3**	**3**	**3**	**1**
Minimum recommended measurement hours for model validation	v_{in} to $v_r - 2$ **3 h**				$v_r - 2$ to $v_r + 2$ **3 h**			$v_r + 2$ to $\frac{(v_r + 2) + v_{out}}{2}$ **3 h**			$\frac{(v_r + 2) + v_{out}}{2}$ to v_{out} **1 h**			
NOTE The recommended number of time series at each wind speed bin is given in the last but one row. The actual number of measurements can be updated in the white cells.														

Table 4 – Capture matrix for power production plus occurrence of fault

Power production plus occurrence of fault			
Time series length	**2 min**	**2 min**	**2 min**
Wind (m/s) Fault condition	$v_{in} < v < v_r - 2$ m/s	$v_r - 2$ m/s $< v < v_r + 2$ m/s	$v_r + 2$ m/s $< v$
Fault No. 1	**2**	**2**	**2**
Fault No. 2	**2**	**2**	**2**
…………..			
Fault No. *n*	**2**	**2**	**2**

NOTE The recommended number of time series at each fault condition is shown in the grey elements. The actual number of measurements can be filled in the white cells.

Table 5 – Capture matrix for parked condition

Parked (standing still and/or idling)			
Time series record length	**Minimum 2 min**		
Parking modes	All design driving parking modes (for example, idling, standstill)		
Yaw angles	At least the two most unfavourable angles		
Record mean wind speed ranges	(v_{in} to $v_r - 2$ m/s)	($v_r - 2$ m/s to $v_r + 2$ m/s)	above $v_r + 2$ m/s
Minimum total time	20 min	20 min	20 min
Actual number of measurements			

Table 6 – Capture matrix for normal transient events

Normal start-up and shut-down events				
Event		(v_{in} to $v_r - 2$)	($v_r - 2$ to $v_r + 2$)	above $v_r + 2$
Start-up	Recommended number	**3**	**–**	**3**
	Actual measured wind speed (m/s)			
Normal shut-down	Recommended number	**3**	**3**	**3**
	Actual measured wind speed (m/s)			

NOTE 1 The actual measured wind speed is the average over the duration of the transient event.

NOTE 2 The actual wind speed measured during the transient event shall be filled in the white cells.

Table 7 – Capture matrix for other than normal transient events

Other transient events				
Event		**Most critical wind speed**		
Grid failure	Recommended number	**3**		
	Actual measured wind speed (m/s)			
Emergency shut down	Recommended number	**3**		
	Actual measured wind speed (m/s)			
Overspeed combinations	Recommended number	**3**		
	Actual measured wind speed (m/s)			
Other design critical transients	Recommended number	**3**		
	Actual measured wind speed (m/s)			

NOTE 1 The actual measured wind speed is the average over the duration of the transient event.

NOTE 2 The actual wind speed measured during the transient event shall be filled in the white cells.

3.3 Quantities to be measured

3.3.1 General

The relevant physical quantities to be measured in order to characterize the loading of wind turbines can be classified into

– load quantities (for example, blade loads, rotor loads and tower loads);

– meteorological parameters (for example, wind speed and direction, ambient temperature and air pressure and other);

– operational parameters (for example, power, rotational speed, pitch angles, yaw position, azimuth angle).

In the following subclause, a more detailed specification is given for the various categories of measurement quantities.

3.3.2 Load quantities

The measurements aim at the determination of the fundamental loads on the wind turbine. These are the basic loads on crucial locations of the wind turbine construction from which the loading in all the relevant wind turbine structural components can be derived. The fundamental loads to be measured are listed in table 8. Figure 1 indicates the load vectors on the wind turbine structure. The co-ordinate systems to use for the description of the load quantities are given in annex A. If specific loads such as actuator loads (for example, yaw and pitch) are critical to safe operation then they should also be measured.

Table 8 – Wind turbine fundamental load quantities

Load quantities	Specification	Comments
Blade root loads	Flap bending Lead-lag bending	Blade 1: mandatory Other blades: recommended
Rotor loads	Tilt moment Yaw moment Rotor torque	The tilt and yaw moment can be measured in the rotating frame of reference or on the fixed system (for example, on the tower)
Tower loads	Bottom bending in two directions	

3.3.3 Meteorological parameters

Table 9 lists the meteorological quantities to be measured in load measuring programmes.

Table 9 – Meteorological quantities

Quantity	Importance level	Comments
Wind speed	Mandatory	At hub height
Wind shear	Recommended	
Wind direction	Mandatory	At hub height
Air temperature	Mandatory	Influences material properties
Temperature gradient	Recommended	
Air density	Mandatory	Derived from air temperature and air pressure (which may be derived from the altitude taking into account ISO atmosphere)

3.3.4 Wind turbine operation quantities

Table 10 lists the operation quantities which are or may be required.

Table 10 – Wind turbine operation quantities

Quantity	Importance level	Comments
Electrical power	Mandatory	
Rotor speed	Mandatory	
Pitch angle	Mandatory	Only for variable pitch turbines
Yaw position	Mandatory	
Rotor azimuth	Mandatory	If yaw and tilt moment are measured on the rotor shaft
Grid connection	Recommended	
Brake status	Recommended	
Wind turbine status	Useful	Relevant parameters may be derived from control panel of wind turbine

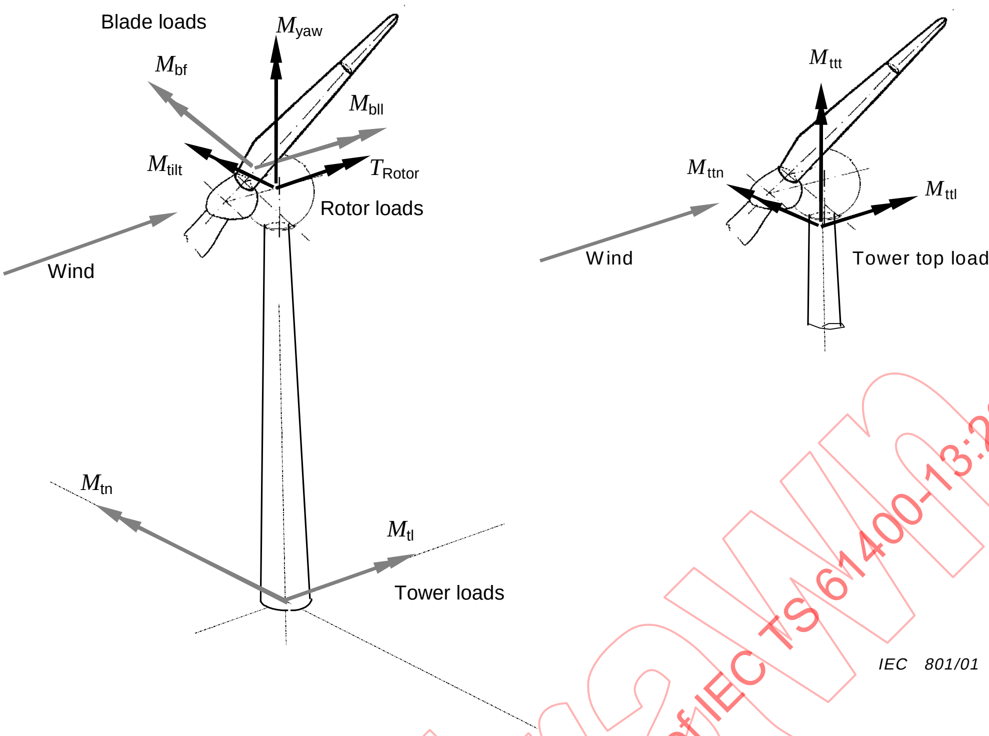


Figure 1 – Fundamental wind turbine loads: tower base, tower top, rotor and blades

4 Measurement techniques

4.1 General

In this clause, the measurement techniques for the various types of quantities in load measurement programmes are described. These techniques include

– instrumentation;
– calibration;
– signal conditioning (where relevant).

If, with respect to calibration, for a particular type of sensor, nothing is specifically mentioned, sensor calibrations should be performed and documented.

Furthermore, this clause gives recommendations with respect to the data-acquisition methods in load measurement programmes.

4.2 Load quantities

4.2.1 Sensors

This subclause deals with load sensors, selection of suitable locations and recommended deployment procedures. Before dealing with the specifics of measuring loads on wind turbines, the following points will be highlighted:

– recommended types of load sensors;
– general considerations for sensor location;
– calibration procedures to ensure accurate and reliable performance of the instrumentation.

4.2.1.1 Types of sensors

A load sensor is a device that directly or indirectly measures the load experienced by a system or component. Typical devices include, but are not limited to

– strain gauge bridges;
– load cells/torque tubes (including piezoelectric cells);
– accelerometers, velocity, rotation and displacement transducers.

For wind turbines, it will seldom be possible to place a load cell in a main load path. For this reason, strain gauges applied to the structure are selected as the recommended type of sensor. It is recommended that the strain gauge output be related direct to an applied load level. This is achieved by establishing static calibration relationships. It is important to realize that dynamic behaviour of the structure or component can modify this relationship so that the strain gauge will indicate gross internal loads rather than externally applied loads. In strain gauge application, it is particularly important to avoid wire temperature effects and cross-sensitivity and to ensure proper temperature compensation. Cross-sensitivity is the undesirable characteristic of a measurement system of being sensitive to different load sources, making it difficult or impossible for the system to differentiate between them. Full strain-gauge bridge designs offer good scope for reduction of cross-sensitivities and temperature effects and are to be preferred for most wind turbine applications.

NOTE Accelerometers or displacement transducers can also be used to measure applied loads indirectly, relying on a knowledge of the inertia or stiffness of the structure. For a dynamic system, interpretation will depend upon whether the device is well below, at, or well above, a resonant frequency. However, this method is difficult. It requires very accurate descriptions of the structural mass and stiffness and is therefore prone to significant error.

4.2.1.2 Choice of sensor location

In the process of selecting sensor positions for the measurement of gross structural loads, it is recommended to choose a location which

– has a high strain per unit load level;
– provides a linear relationship between stress and load and as such should avoid load introduction paths;
– is in a region of uniform stress (i.e. is not subject to high stress/strain gradients, avoids localized stress raisers or concentrations);
– has space to apply sensors;
– allows temperature compensation;
– is made of material having uniform properties (for example, steel is preferable to composite materials);
– is made of material to which measurement devices can be easily fixed or bonded.

4.2.1.3 Calibration of load sensors (general)

Experimental verification and calibration of strain gauge bridges shall be carried out for all mandatory sensors. It is recommended that the calibration is carried out prior to the actual test. All the mandatory load sensors shall be checked before and after the actual testing period. Ideally, the separate links in the measurement chain should have known individual calibrations.

4.2.1.3.1 Initial calibration

Loads are measured using a sensor (the strain-gauge bridge) and a measurement chain (bridge excitation, signal amplifier, filter and data acquisition system). To avoid the need to recalibrate the sensor after changing an element in the measurement chain, it is recommended that the sensor and the measurement chain be calibrated separately.

a) Calibration of the sensor

To determine the sensor sensitivity (the relation between the load in N or Nm and the sensor output in mV/V) quasi-static calibration loads are applied on the turbine in a number of steps covering the expected load range during turbine operation as much as practically possible. The calibration loads can be applied using well-known masses or using a winch and a load cell secured to the ground, to a crane or to another part of the turbine. Calibration of the sensor and component in a laboratory is also possible. It is recommended to preload the turbine a few times before the initial calibration to get rid of possible residual stresses. During calibration, the applied loads and the corresponding sensor signals shall be recorded for subsequent data treatment. It is recommended not only to determine the output of the sensor as a function of the load for which the sensor is designed but also for other loads to account for the possible effect of cross-sensitivity.

If a load-based calibration is impossible, the sensor sensitivity can be determined analytically using the dimensions and material properties of the structure and the properties of the strain-gauge bridges (configuration and k-values). This analytical approach, however, leads to a higher uncertainty in the sensor sensitivity than the result of a load-based calibration and should not be used with composite materials or complicated cross-sections.

b) Calibration of the measurement chain

The measurement chain from sensor output through the data acquisition system is calibrated by generating known sensor outputs and recording the corresponding readings in the data acquisition system. Known sensor outputs can be generated by mechanical loadings, as described above, but it is much more practical to generate the sensor outputs electrically. This can be done by substituting the sensor temporarily with a dedicated instrument (a strain-gauge bridge simulator) or by shunting one of the strain gauges in the bridge temporarily with a large resistor of, say, 1 000 times the gauge resistance.

4.2.1.3.2 Calibration checks

It is advised that calibration checks of the measurement chain (from sensor to signal) be performed at regular intervals. In cases where it is observed that the calibration data have changed beyond the acceptable limits of uncertainties, the cause of this change has to be established. Calibration checks of the measurement chain can be readily performed in the same way as the initial calibration.

4.2.2 Measurement of blade root bending moments

4.2.2.1 Instrumentation

Flap and lead-lag bending moments shall be measured. For lightning and environmental protection, it is recommended that the sensors be mounted within the blades rather than on the outer surface, where convenient. This will also lead to better protection during handling.

Strain gauges should be applied in such a position that cross-sensitivities between lead-lag and flap-load measurements are minimized. Applying the gauges to a part of the blade root which is as nearly cylindrical as possible may facilitate this. Regardless of the mounting location, cross-sensitivity should be measured and corrected according to B.2.1.

In the case of pitch-regulated turbines, the above advice also applies. However, for consistency, the sets of gauges should be oriented so that they are parallel to and perpendicular to the chord line at 70 % radius.

4.2.2.2 Calibration

The blade-root load sensors should be calibrated by external force application close to the blade tip. Alternatively, the signals for the lead-lag and flap-bending moment in the blade root can be calibrated using the blade mass as a calibration load in case the blade can be pitched over at least 90°. Since the load signals are designed to measure the bending moments in the blade root at the position of the strain gauges, the calibration has to be performed using the values of the mass and centre of gravity of the part of the blade outside the strain-gauge position for the determination of the calibration load. This requires exact knowledge of the distribution of the blade mass per unit length along the blade axis.

It should be noted that using the blade mass to calibrate the loads might limit the calibration load range and result in a higher calibration uncertainty.

4.2.2.3 Calibration check

By rotating the rotor slowly around 360°, the blade mass causes a variation in the lead-lag signal. If pitching is possible, the variation in the flap wise signal can also be measured. The variations have to be measured at initial calibration in order to determine the reference for repeated checks later on. This check shall be done at low wind speeds. When checking the lead-lag moments, it is recommended to yaw the wind turbine 90° in relation to the wind direction.

4.2.3 Measurement of yaw and tilt moment

4.2.3.1 Instrumentation

When instrumenting for the measurement of the rotor moments, a distinction should be made between machines with rotating main shaft and machines with fixed main shaft support (and either an internal transmission shaft, a direct-drive generator, or some other torque-transferring arrangement).

On machines with a rotating main shaft, the tilting and yawing rotor moments cannot always be derived from measurements on the shaft even with proper azimuth recording. In such cases, it is recommended to install gauges for bending moments in the fixed system.

On machines with a fixed rotor shaft support, the tilting and yawing rotor moments can be derived from measurements on the shaft support. Consequently, measurements of bending moments in the tower top and torsion in the tower top are not required to determine the overall moments. They may be needed, however, for more specific component evaluation.

If the yaw and tilt moments are measured at the rotating main shaft in combination with the rotor azimuth signal, it is recommended that the strain gauges be positioned in line with the instrumented rotor blade. If the strain gauges are mounted in the fixed frame of reference, special attention shall be given to their positioning. The structural influence from the yaw system shall be analysed and reported.

4.2.3.2 Calibration

The sensors shall be calibrated by applying an external load. If the loads are measured on the rotor shaft, the load signal for one bending direction should be calibrated at the same time as the blade-root flap-bending moment calibration.

The calibration of the sensor for the other bending direction can be done by using the rotor mass. Both shaft-bending signals should be measured while turning the rotor through one revolution. The calibration of the second shaft-bending moment should be set to give a load amplitude equal to the already calibrated moment.

If the loads are measured on a fixed rotor shaft support or at the tower top, the calibration should be done by applying external loads on a blade in such orientation that a representative range of bending moments is obtained.

4.2.3.3 Calibration check

By yawing the turbine through 360°, the mass of the nacelle and rotor combined with its centre of gravity causes a signal variation. The variation has to be measured at initial calibration to determine the reference for repeated checks later on. The zero point is determined from the mean of the sinusoidal bending moment signal obtained when rotating the nacelle from 0° to 360°. This should be carried out below cut-in wind speed.

If the yaw and tilt moments are measured at the rotary main shaft in combination with the rotor azimuth signal the rotating rotor causes a sinusoidal variation on the signals. This variation has to be measured at the initial calibration by rotating the rotor at very low rotor speed (idling) at wind speeds below cut-in wind speed.

4.2.4 Measurement of the rotor torque

4.2.4.1 Instrumentation

The strain gauges for measuring the torque of the main shaft should consist of a full bridge with pairs of gauges on opposite sides of the shaft. Using the bridge only on one spot of the shaft surface, shear due to bending and transverse load will be interpreted as torque.

4.2.4.2 Calibration

The calibration of the rotor torque load sensors should be performed by applying a load on the blade.

4.2.4.3 Calibration check

The shaft torque can be checked against the electric power signal, taking into account the efficiencies of the gear box and the generator system. During standstill of the turbine below cut-in wind speed, the zero point of the signal can be checked regularly.

4.2.5 Measurement of tower base bending

4.2.5.1 Instrumentation

The bending moments at the tower base shall be measured in two perpendicular directions for a tubular tower. In the case of a guy-wire supported tower, the tower base measurements may be replaced with measurements above the guy-wire attachment point. If the guy ropes are the main structural elements then the force in each rope should be monitored.

A lattice tower will require strain measurements in all supporting legs to arrive at the resultant tower base load for all wind directions. A special assessment of the strain pattern in the lattice tower and the consequence for the measurements shall be performed.

4.2.5.2 Calibration

An external load shall be applied for calibration of tower base bending, either from the ground or from a crane or neighbouring wind turbine. Attention should be paid to additional loading due to the offset of the nacelle and rotor centre of gravity with respect to the tower axis.

Because of tower size and position, the comment about analytical calibration (see 4.2.1.3) may apply.

4.2.5.3 Calibration check

By yawing the turbine through 360°, the mass of the nacelle and rotor combined with its centre of gravity cause a signal variation. The variation has to be measured at the initial calibration and shall be repeated periodically thereafter. The zero point is determined from the mean of the sinusoidal bending moment signal obtained when rotating the nacelle from 0° to 360°. This should only be carried out below cut-in wind speed.

4.3 Meteorological quantities

4.3.1 Wind speed and wind direction

4.3.1.1 Instrumentation

Cup anemometers are recommended for wind speed measurements. Their range should be larger than for power curve measurements. The anemometers should be able to record wind speeds up to 50 m/s in order to capture extreme wind situations during the load measurements. The distance constant of the anemometers used shall be less than 5 m. Mounting and positioning of anemometers on the mast should be done according to IEC 61400-12.

The wind direction should be measured with a wind vane mounted according to IEC 61400-12.

It is also acceptable to use a nacelle-mounted anemometer and a wind vane on a lower mast if a suitable calibration for undisturbed flow has been completed. Since the calibration will depend on the operating parameters of the turbine, the calibration relation shall specifically account for any varying operating parameters of the turbine, such as rotor speed, pitch angle, etc. and for variation in external conditions, in particular incident flow angle and turbulence. Such a calibration shall be made on the same or an identical turbine. The wind sensors have to be mounted at the identical location on the nacelle as at the reference turbine.

The uncertainty analysis shall account for any significant increase in uncertainty caused by the use of a nacelle-mounted anemometer.

Wind farm operation and relevant obstacles in the vicinity of the turbine have to be taken into account carefully during the evaluation of the data.

4.3.1.2 Calibration

Calibration of met-mast anemometer

Anemometer calibration should be carried out according to the recommendations given in point 4 of clause 6 and/or IEC 61400-12.

Anemometer calibrations should be traceable to national standards. In addition, the calibration laboratory should have verification of the comparability of their calibrations with other recognized calibration facilities through a programme of interlaboratory comparisons.

Calibration of nacelle-mounted anemometer

The nacelle-mounted anemometers have to be calibrated in the same way as the met-mast anemometers. Additionally, a calibration function between both the nacelle and the undisturbed anemometer has to be evaluated and documented. This is not only necessary for the average wind speed, for example 10-min averages, but also for the relation of the standard deviation in order to assess the turbulence intensity. Special attention is to be drawn if the turbine is out of operation, where a different calibration relationship applies.

4.3.2 Air density

If for the determination of the air density, the air temperature and air pressure are measured, the guidelines given in IEC 61400-12 should be followed.

4.4 Wind turbine operation parameters

The description of the measurements of the wind turbine operation parameters (electrical power, rotor speed, blade pitch angle, yaw position, rotor azimuth angle, turbine status, etc.) is not given because these measuring techniques are very wind turbine specific. Some of the signals are provided by the control system. The required accuracy for the wind turbine operation signals is specified in 4.6.

Turbine status information (for example, grid connection, emergency shut-down, protection system activation, etc.) is necessary in order to properly categorize recorded data when unattended. Such information may also be useful for a trigger signal for automatic data acquisition.

4.5 Data acquisition

A digital data acquisition system shall be used to collect and store time series and statistical data. The data acquisition shall satisfy the following requirements:

– analogue filters with cut-off frequency at least three times higher than any significant frequency in the relevant signal to reduce noise and aliasing effects;
– the sampling frequency shall be at least eight times higher than any significant frequency in the relevant signal;
– the data conversion range of any measurement channel shall be sufficiently wide to avoid saturation (considering the whole measurement chain of transducer, analogue converter and a/d converter);
– resolution of all digital components of the measurement for critical signals 12 bits or higher.

In addition to the requirements, there are the following desirable features:

– summary statistics such as average, standard deviation minimum and maximum can be calculated automatically in a pre-process;

– continuous data acquisition and storage of time series and statistical data;

– intelligent storage strategy which gives, for example, the possibility to programme the capture matrix;

– display to check on-line data of selected channel(s).

Guidance for issues regarding signal conditioning for load sensors may be found in Report EUR 16898 EN [4][1].

4.6 Sensor accuracy and resolution

Accuracy is an estimation of how well measurements of a test channel correspond to a known standard. The measurement accuracy of a channel is dependent upon the quality of its calibration. Calibrations should be performed with the same instrumentation used to record the test data. This provides integral calibration of all components along the data measurement path including sensors, cables, signal conditioner, and A/D converter. It is recommended that multiple calibrations be performed under conditions similar to those expected during actual measurement.

The best way to ensure measurement accuracy is to measure the full channel response direct using an external reference that produces a known result. With this technique, all components along the data path are calibrated together and the accuracy of the full data path can be determined. The accuracy is the standard uncertainty of the sensitivity coefficient for that calibration.

For many types of measurements, it is not possible to directly calibrate the full measurement path simultaneously. The alternative requires system components to be calibrated separately. The uncertainty of the transducer is determined by pre-test and post-test calibrations to ensure that it remained within tolerance during the test. The uncertainty of the electronic portion of the signal path is determined by replacing the sensor with a known reference.

The load measurement calibration uncertainty is defined by the uncertainty in the principal element of the calibration matrix (for example, U_{cA1}/A_1, equation B.6). The target value is 3 %. (This yields a 95 % confidence range of ±6 %). Table 11 lists target values for the standard uncertainties for non-load quantities.

Table 11 – Target standard uncertainties for the various non-load quantities

Quantity	Target value	Method of verification
Meteorological parameters		
Wind speed	0,2 m/s	See IEC 61400-12
Wind direction	5°	End-to-end calibration
Ambient temperature	2 K	See IEC 61400-12
Air pressure	10 hPa	See IEC 61400-12
Operational parameters		
Electrical power	1 % of rated value	See IEC 61400-12
Blade pitch angle	0,3°	End-to-end calibration
Rotor speed	1 % of rated value	End-to-end calibration
Yaw position	5°	End-to-end calibration
Rotor azimuth	2°	End-to-end calibration

[1] Figures in square brackets refer to the bibliography.

The following items should be included for the documentation of measurement uncertainty for each channel:

– sensor calibration sheet;
– calibration sheet of external measurement standard;
– calibration data (plot of signal versus external measure, sensor sensitivity, standard uncertainty of sensitivity);
– conditions of calibration (date, ambient temperature, wind speed, etc.);
– configuration of data acquisition system (sample rate, gain, resolution, etc.).

The determination of the measurement uncertainty should be performed and reported according to annex B.

5 Processing of measured data

5.1 General

In this clause typical practices used to determine the wind turbine's dynamic behaviour in relation to the wind characteristics are presented. Specifically, the following issues are discussed: data validation, time series analysis, summary load statistics, generation of lifetime load spectra based on rainflow counted ranges and estimation of equivalent loads.

5.2 Data validation

The validity of the measured quantities as well as of the calculated magnitudes, for example, the resulting rotor loads from shaft bending moment measurements, shall be checked in order to exclude any erroneous recordings. Only data of documented validity may be used in further analysis.

In general, data shall be rejected if they do not meet criteria related to sensor calibration, sensor operational ranges and noise.

If data were recorded under abnormal ambient conditions, that are not classified as extreme conditions (for example, rain, ice), they should be segregated into a special category for possible further analysis.

The first stage validation of measured time series should be performed during commissioning of the measuring programme and is based on raw data recordings at the specified or higher sampling rates. During the measurement period, time series data shall be periodically checked in order to ensure high quality and repeatability of the test results. Furthermore, a second stage data validation shall be performed based on the total assembly of the statistics of the measured and calculated quantities. Regular visual inspection of the data is recommended to spot anomalies that otherwise would not be detected.

The main issues related to data validation are described in the following.

– *Identification of invalid measurements due to obstacle shadowing*: wind speed and direction measurements while the sensors operate within the wake of the tested machine or other obstacles should be rejected.
– *Exclusion of any measurements outside operational limits*: the operational limits of sensors, transfer (for instance the telemetry system) and acquisition system should not be violated. Special attention should be paid in cases of extreme conditions.
– *Check on calibration*: valid data shall be based on suitable calibrations as described in clause 4. The first part of the data validation is a formal check that calibrations have been carried out.

– *Drift*: drift of zero points may be identified from measured data statistics. Zero drift due to temperature effects can be large, especially on the blade measurements, and should be checked, documented and accounted for. If any data correction is applied, it should be reported in detail and taken into account during uncertainty estimations. Drift is best identified by monitoring signal levels in low wind speed conditions.

– *Erroneous application of sensor calibration constants*: attention should be paid in cases where changes in sensors, amplification or acquisition settings are made during the measuring period.

– *Presence of noise:* valid data should not be affected by noise to such an extent that the target signal/noise relationship is not met for any significant frequency of the relevant signal. Corrective actions may be essential in order to compensate for the limited presence of noise. For each measuring channel a threshold should be defined that will characterize a spike attributed to noise. Isolated spikes may be recovered by using the two adjacent valid measurements and an interpolation formula. Records including numerous isolated spikes, unrecoverable adjacent spikes or spike peaks reaching saturation should be rejected. If spikes are removed from the data series, the procedure shall be recorded. Data may be accepted as valid even though other measurement channels do not meet the noise validation criteria, provided such other channels are not necessary for the data analysis. If spikes are detected, the summary statistics of that channel shall not be used.

– *Unrealistic differences* between comparable quantities: in several cases (for example, measurements of tower base moments or shaft-bending moments), a comparison of the recordings of the two independent sensor sets may be made. If unexplainable differences are observed, the instrumentation should be re-checked and the suspect data should be excluded.

It should be noted that excluded time series might be useful in the analysis of special conditions.

Further validation is performed after completion of the fatigue analysis calculations. Checks on specific magnitudes that present a consistent variation may reveal erroneous recordings. These magnitudes include the equivalent loads and the total number of alternating cycles in each record.

5.3 Time series and load statistics

Plotting the measured and calculated load time series serves the following purposes:

– signal validation checks;

– calibration;

– characterization of wind turbine dynamic loading under normal conditions and transient events;

– reporting of measurement campaign.

A typical presentation of a recording is described in C.2.1.

The statistical information of all measured and calculated loads, accompanied by the respective wind and wind turbine operational magnitudes should be presented with respect to mean wind speed. The presentation of the statistics, namely mean, maximum and minimum values as well as standard deviation – all defined within the time frame described by the capture matrix – serves the following purposes:

Characterization of wind inflow: the inflow, described by wind speed statistics, air properties and turbulence intensity, characterizes the conditions under which the test was performed.

Characterization of wind turbine static and dynamic loading under normal conditions: the performance of the wind turbine is characterized by the load and operational mean and range of variation scatter plots. Furthermore, the statistics of the assembly of the recorded time series, as captured by the matrix, are qualitatively assessed in order to justify that the collected time series adequately represent the measurement campaign.

Validation checks: the consistency of measurements is validated against the load mean curves and ranges of variation. Faulty operation of instrumentation, data acquisition system or analysis software may be clearly depicted from the measurement statistics.

Reporting of measurement campaign: representative scatter plots shall be included in the test report.

In addition, frequency analysis such as power spectral densities of relevant channels should be plotted to characterize wind turbine dynamics (see C.2.3).

A typical presentation of wind, wind turbine operational as well as wind turbine load statistics is described in clauses C.3 to C.5.

5.4 Load spectra

5.4.1 General

A minimum of collected data sets has to be available in order to carry out a fatigue analysis from measured time series. The requirements on the data-base, including the amount of data required in the different wind speed and turbulence bins of the capture matrix are given in clause 3.

Caution should be taken that slow variation in wind speed may result in non-representative high turbulence intensity estimates, for example steady increase or stepwise changes in wind speed during the 10 min. A representative set of measurements can be achieved either by selecting only 10-min samples with a steady mean wind speed or by high-pass filtering the wind speed before calculating the turbulence intensity. Any low-frequency filtering shall be described in detail in the report and shall be chosen so that similar filtering applied to the wind model used in the design does not significantly affect resulting design loads.

Guidance on extrapolation of spectra of measured loads to other turbulence conditions is given in annex D.

5.4.2 Rainflow counting

Fatigue load spectra for each measured time history may be calculated according to the rainflow counting methodology. Such measured fatigue load spectra can be compared to spectra for similarly defined loads and similar external conditions used in the design calculations. The procedure of the rainflow counting (described in reference 1 of clause 6) includes the following steps:

a) removal of load points from the sequence that do not present a local minimum or maximum considering the two adjacent points;

b) counting and removal of the full cycles;

c) counting of the residual cycles as half-cycles.

The number of divisions of the load range shall be at least 50 in order to achieve sufficient resolution. If the classification is constant then the expected maximum of the load ranges should be chosen so that it will fill as many divisions as possible. Alternatively, the classification may be different for each recording and depend on the maximum range found in each recording.

The rainflow counting may be used in order to calculate fatigue spectra in different formulations, namely one dimensional spectra (load ranges versus number of cycles) or two dimensional (load from level i to load level j versus number of cycles or mean load i with load range j versus number of cycles).

A typical presentation of one dimensional fatigue spectra is presented in figure C.7, for representative blade, shaft, rotor and tower loads.

5.4.3 From rainflow matrices to load spectra

To determine the load spectra corresponding to lifetime operation, knowledge of the distribution of external and operational conditions over the design lifetime of the turbine is required. Data of this type will typically take the form of a wind speed distribution and information on the number of specific events (starts and stops, faults, yaw activity, etc.) which the turbine is expected to see over its lifetime. This is often referred to as the "duty cycle" [1]. From this, the total lifetime number of occurrences or duration of each steady-state operation and transient event load case can be determined. A weighting factor is then derived for each load case to scale the number of occurrences of each element in the measurement load case rainflow matrices to the lifetime equivalents. The lifetime load spectra are then based on the summation of the weighted rainflow matrices. This procedure does not account for the low cycle fatigue loading resulting from the transition between load cases. A simple method to quantify the low cycle fatigue effects is available [5] which takes account of both the load case transitions and the order in which they occur.

5.5 Equivalent loads

The concept of equivalent load is a convenient, short-hand description of the fatigue impact of a given load measurement time history. The equivalent load is conceptually the single load amplitude that, when applied with the total number of cycles in a given time history appearing at a given frequency (for example, 1 Hz), does the same fatigue damage as the sum of all the different rainflow-counted load amplitudes in the measured load spectrum. The great advantage of the equivalent load is that it provides a single descriptor of the fatigue damaging potential of a particular loading during a given time period. Therefore, it allows direct comparison of the fatigue damage during different operating conditions (free wind, wake, high turbulence, etc.), and it allows the direct comparison of simulated and measured fatigue loads. Specifically, the equivalent load is the weighted average rainflow range, with the S-N-curve slope, m, for the relevant material as the weighting exponent. Material fatigue properties are assumed to be described by a log-log formulation such as

$$N = CS^{-m}$$

where

N is the number of cycles to failure at load amplitude level S;

C and m are material properties.

The S-N-curve slope, m, should represent the relevant materials, for example, values of 3,5 for welded steel, 6,8 for nodular cast iron, and 10 for glass-reinforced plastic.

The determination of the equivalent load also requires the prior selection of a corresponding equivalent number of cycles. The equivalent number of cycles should preferably represent a typical frequency for the given load type. For example, the equivalent number of cycles for the lead-lag blade-root bending moment may reasonably be selected to correspond to the 1p number of cycles, and the equivalent number of cycles for the tilting rotor moment may reasonably be selected to correspond to the blade-passage frequency. It also may be convenient to use 1 Hz. The equivalent load is defined by the expression

$$R_{eq} = (\Sigma R_i^{m}\, n_i/n_{eq})^{1/m}$$

where

R_{eq} is the equivalent load;

R_i is the load of the ith class of the fatigue load spectrum;

n_i is the number of cycles in the ith class of the fatigue load spectrum;

n_{eq} is the equivalent number of cycles;

m is the S-N-curve slope for the relevant material.

Because not all material fatigue properties can be well fit by the log-log form of the S-N curve, and because the equivalent load estimation does not account for different mean-load levels for each measured load cycle, the equivalent load cannot be thought of as an exact estimate of the fatigue damage. It is, however, a good estimate of the relative damaging potential of different load samples at a common location, and is therefore a very useful descriptive statistic.

6 Reporting

The proposed reporting format should provide the reader with answers to all the W-questions – why, what, where, when, who, etc. The following general table of contents is proposed:

1 Introduction

What is measured, and why, in broad terms.

2 Wind turbine

1.1 Photograph of test turbine

1.2 Technical data

The format and extent of the technical description should be in accordance with the requirements of the IEC 61400-12.

3 Measurement site

3.1 Geographical location

Sufficiently detailed information to allow the reader to locate the test machine.

3.2 Local topography

Topographical details corresponding to the reporting requirements of IEC 61400-12.

4 Instrumentation

4.1 Measurement system arrangement

The overall set-up of the measurements.

4.2 Transducers and converters

Location and type of each transducer. Strain-gauge locations identified on a figure of the machine. More specific location descriptions (photographs) may be included in an annex. Location and type of each converter. Transducers and converters to be identified by serial number, where relevant.

4.3 Data acquisition system

Type of acquisition system (computer, A/D conversion type and resolution). Software description. Type and settings of capture matrix. Sampling rate and storage arrangements.

5 Calibration

Due to the extent of work often required in calibration, details may be shifted to an annex (for example, calibration certificates, regression analysis, etc). However, the entire calibration arrangements should be outlined in the main report.

5.1 Sensor calibrations

Descriptions of all calibrations carried out off-site, for example anemometers, power transducers, etc.

5.2 Calibration of measurement chains

Descriptions of all line calibrations carried out on site, for example, with artificial anemometer signals from frequency generators, strain simulations, etc.

5.3 Load calibrations

Descriptions of all load calibrations carried out on site, for example, by the application of loads through load cells.

5.4 Summary of signal conversions

6 Database

6.1 Capture matrix

Set-up values for the capture matrix – wind speed and turbulence intervals, wind direction ranges, etc.

6.2 Data validation

Sorting and acceptance criteria. Description of rejected data.

6.3 Resulting database

Specification of data left available after validation. Numbers of files, etc.

7 Time histories and load statistics

7.1 Plots of typical time histories for all relevant channels at different wind speeds.

7.2 Plots of summary load statistics (see annex C).

8 Turbine dynamics

8.1 Analysis methods

Description of methodology and algorithms – resolution, averaging, weighting, etc.

8.2 Frequency spectra for shut-down turbine

Plots of frequency spectra for all relevant channels.

8.3 Frequency spectra for operating turbine

Plots of frequency spectra for all relevant channels at low and high wind speeds.

8.4 Interpretation of dynamics

Logic procedure in identification of frequencies, table of conclusions.

9 Fatigue loads

9.1 Analysis methods

Description of methodology and algorithms – resolution, averaging, weighting, etc.

9.2 Load spectra

Plots of load spectra for all relevant channels. Tables may be shifted to an annex.

9.3 Equivalent loads

Plots of equivalent loads versus wind speed for all relevant channels at constant turbulence and yaw error.

10 Uncertainty estimation

10.1 Calibration uncertainty

10.2 Uncertainty of measured loads, time series, mean loads, equivalent ranges and annual spectra

11 References

Appendices

Annex A
(informative)

Co-ordinate systems

A.1 General

All co-ordinate systems are right-handed Cartesian systems.

A.2 Blade co-ordinate system

The blade co-ordinate system is fixed to the blade. In general, its origin is the centre of the blade flange.

z_b-axis — Parallel with the pitch (longitudinal blade) axis, pointing towards the blade tip.

y_b-axis — Parallel to the zero pitch line at the blade root, supplied by the blade manufacturer and pointing towards the trailing edge. If this line is non-existent, then the y_b-axis is parallel to the chord line at 70 % of the blade span, pointing towards the trailing edge.

x_b-axis — Defined such that the system x_b y_b z_b is right-handed.

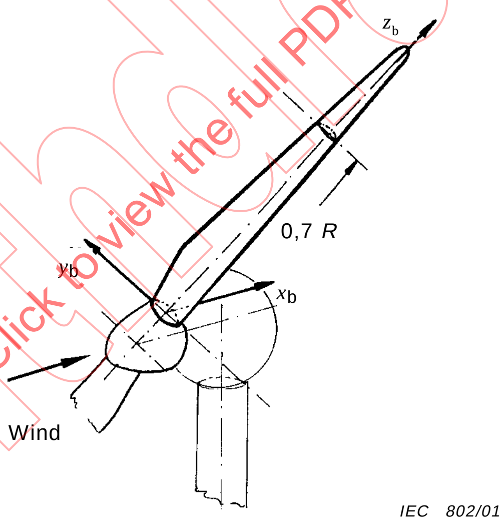


Figure A.1 – Blade co-ordinate system

A.3 Hub co-ordinate system

To transform the blade co-ordinates into the hub co-ordinate system, the cone and the pitch angles and the distance between blade flange and rotor centre have to be taken into account. One blade should be chosen as the reference blade.

The hub co-ordinate system rotates with the main shaft. The origin is on the main shaft in the plane perpendicular to the main shaft that contains the blade co-ordinate origin of the reference blade.

x_h-axis — Parallel to the main shaft, positive in the downwind direction.

z_h-axis — Parallel to the rotor disk plane through the reference blade origin.

y_h-axis — Defined such that the system x_h y_h z_h is right-handed.

In case of a teetering hub, the hub origin is defined at zero teeter angle.

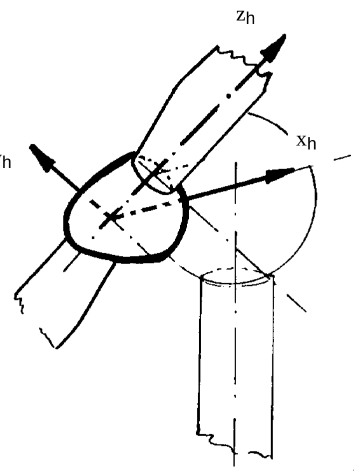


Figure A.2 – Hub co-ordinate system

A.4 Nacelle co-ordinate system

When transforming the hub co-ordinates into the nacelle co-ordinate system, the rotor azimuth and tilt angles and the relative position of the hub origin and nacelle origin have to be taken into account.

The nacelle co-ordinate system has its origin on the yaw axis at the closest point to the rotor shaft centre axis.

x_n-axis	Parallel with the horizontal projection of the rotor axis.
y_n-axis	Horizontal, defined so that x_n, y_n, z_n form a right-handed system.
z_n-axis	Vertical, pointing up.

The nacelle co-ordinate system yaws with the nacelle.

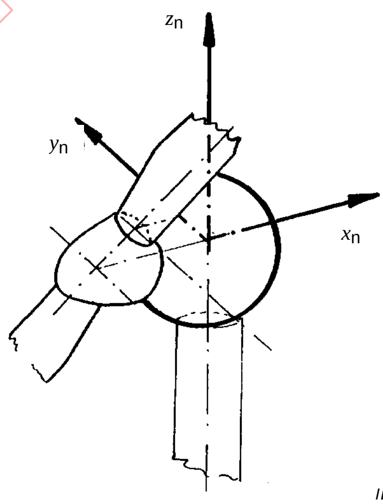


Figure A.3 – Nacelle co-ordinate system

A.5 Tower co-ordinate system

In order to transform the nacelle co-ordinates to tower co-ordinates, the nacelle yaw, tilt, shaft off-set and distance between the nacelle origin and the tower base have to be taken into account.

The tower co-ordinate system has its origin at centre of the tower base.

z_t-axis Co-axial with the tower axis.

x_t-axis to be defined as convenient (a.o. according to the site and the shape of the tower cross-section).

y_t-axis defined by right-hand system of z_t and x_t.

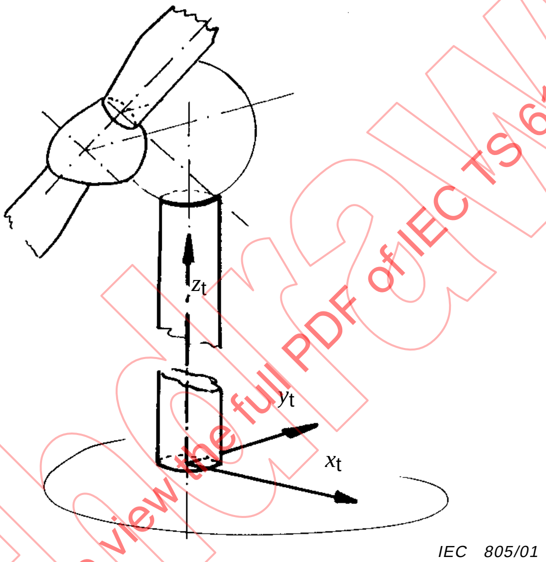
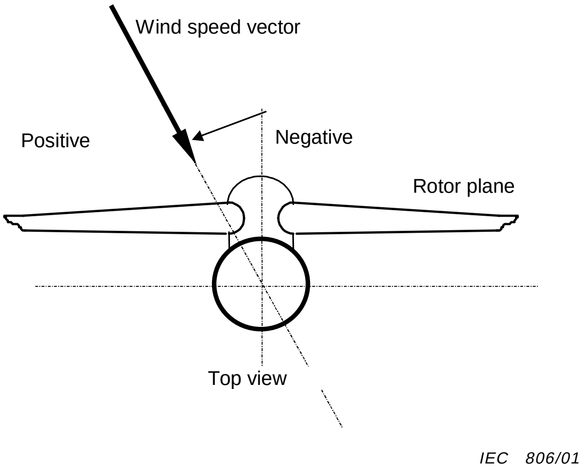


Figure A.4 – Tower co-ordinate system

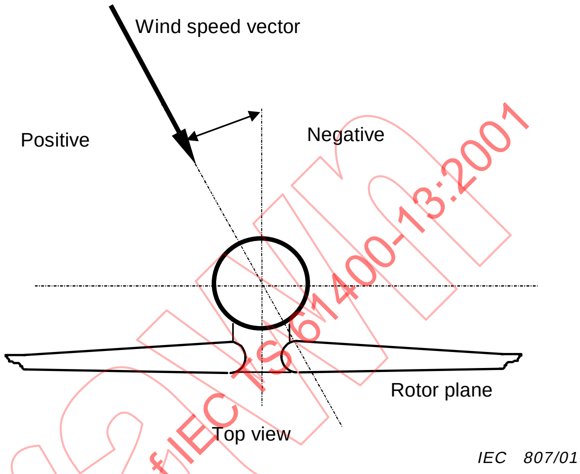
A.6 Yaw misalignment

The yaw misalignment is defined as the angle between the horizontal projections of the centre line of the main shaft and of the wind speed vector.

In figure A.5, the yaw misalignment is shown to be positive.



Upwind machine

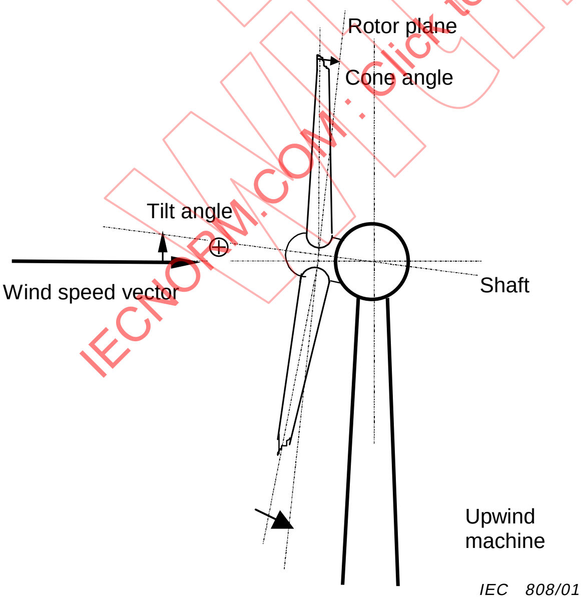


Downwind machine

Figure A.5 – Yaw misalignment

A.7 Cone angle and tilt angle

The cone angle and tilt angle are shown in figure A.6.



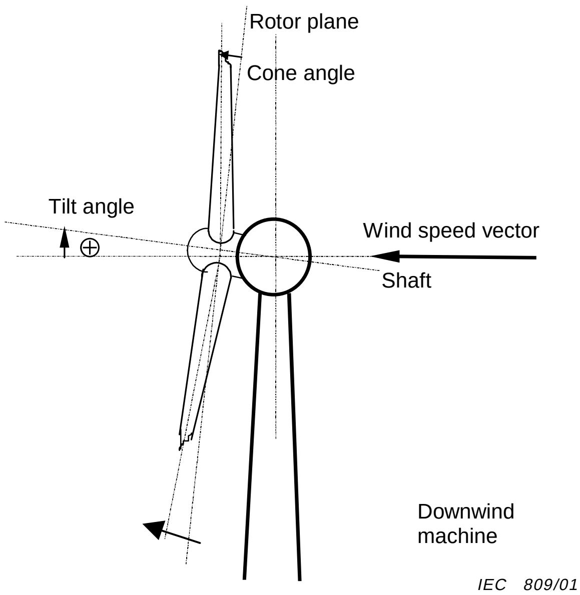


Figure A.6 – Cone angle and tilt angle

A.8 Rotor azimuth angle

The rotor azimuth angle varies from 0° to 360°. The zero angle 0° is defined with the reference blade pointing up.

A.9 Blade pitch angle

The blade pitch angle is the relative rotation of the y_b-axis with respect to the hub co-ordinate system. It is defined as positive towards feather and negative towards stall.

Annex B
(informative)

Procedure for the evaluation of uncertainties in load measurements on wind turbines

List of symbols

A	coefficient in calibration matrix
a	maximum error
c (sub)	combined
c (super)	during calibration
cal	due to calibration uncertainty
D	coefficient in inverted calibration matrix
e	edgewise
f	flatwise
F	calibration force
i	index (general)
L	distance between calibration load and strain gauge
M	bending moment
n	index in Monte Carlo procedure
n_{eq}	equivalent number of cycles per 10 min
N	number of entries per bin
$1/m$	slope of the material Wöhler curve
r	correlation coefficient
Ran	random value
R_{eq}	equivalent load range
$stdev$	standard deviation
sig	due to signal uncertainty
S	signal
s	type A uncertainty
u	type B uncertainty
U	standard uncertainty in final result
v	wind speed
*	modified value in Monte Carlo procedure
x	direction of calibration load w.r.t. blade axis
δ	partial derivative
θ	direction of calibration load w.r.t. blade chord

B.1 General procedure

B.1.1 Standard uncertainty

The uncertainty in wind turbine load measurements is determined in compliance with the ISO Guide to the expression of uncertainty in measurement. In this guide, the uncertainty of a measured quantity is called the standard uncertainty of that quantity. It is assumed that the measured quantity is characterized by a normal (Gaussian) probability distribution with the measured value as mean value and with the standard uncertainty as standard deviation. The ISO guide distinguishes type A uncertainties and type B uncertainties.

– Type A uncertainties (symbol s_i) are uncertainties that can be determined by analysing a series of repeated measurements. If a stationary quantity is measured n times, the type A uncertainty of the individual measurement result is calculated as the standard deviation of the n results. The standard uncertainty of the mean value of the results is calculated as this standard deviation divided by the root of the number of observations ($s_i = stdev/\sqrt{n}$).

– Type B uncertainties (symbol u_i) are uncertainties that cannot be determined by repeated observations. The determination is based on judgement of all available information on the uncertainty of the quantity. This information can be the general knowledge of the behaviour of materials or instruments or the instrument specifications of manufacturers.

In case the standard uncertainty is specified by the instrument manufacturer or by a handbook or by any other source as an uncertainty interval with associated confidence level, one can assume a normal distribution and calculate the corresponding standard deviation. In case the source quotes a maximum error, a one can assume a rectangular probability distribution with a width of $2a$ and determine the standard uncertainty as

$$u_i = a/\sqrt{3}.$$

B.1.2 Combination of standard uncertainties

In most situations, the final result of an experiment is determined by combining measured quantities (for example, torque and rotational speed to determine shaft power) or hand book data (for example, elasticity coefficient). The combined type A uncertainty of the final result (s_c) is determined by combining the type A uncertainties of the input quantities. The combined type B uncertainty (u_c) is determined by combining the type B uncertainties of the input quantities. The standard uncertainty of the final result is then determined as $u = \sqrt{s_c^2 + u_c^2}$.

Combination of standard uncertainties can be done analytically or numerically.

Analytical combination of standard uncertainties is done in case the final result (y) is determined from the input quantities (x_1, x_2, .. x_n) analytically:

$y = f(x_1, x_2, .. x_n)$

$$s_y^2 = \sum_{i=1}^{n} \left(\frac{\delta y}{\delta x_i} \right)^2 s_{x_i}^2 + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\delta y}{\delta x_i} \frac{\delta y}{\delta x_j} \mathrm{cov}(x_i,x_j) \qquad \text{(B.1)}$$

$\mathrm{cov}(x_i,x_j) = r(x_i,x_j)\, s_{x_i}\, s_{x_j}$

$r(x_i,x_j)$ = correlation coefficient between x_i and x_j

The correlation coefficient of two input quantities is a measure for the mutual dependency of their uncertainties. The correlation coefficient can have values between –1 (full negative dependency, for example, by approximation the uncertainties in the slope and offset parameter resulting from a linear fit) and +1 (full positive dependency, for example, the uncertainties in air pressure and air density). In case the input parameters have no mutual dependency (for example, the uncertainty in wind speed and elasticity coefficient) the correlation coefficient is 0. In many situations, the correlation coefficients can be approximated by 0 or by +1 which simplifies equation (B.1) into

$$r = 0:\ s_y = \sqrt{\sum_{i=1}^{n}\left(\frac{\delta y}{\delta x_i}\right)^2 \times s_{x_i}^2} \tag{B.2}$$

$$r = 1:\ s_y = \sum_{i=1}^{n}\left(\frac{\delta y}{\delta x_i}\right) \times s_{x_i} \tag{B.3}$$

These equations can be applied for the type A uncertainties as well as for the type B uncertainties.

Numerical combination of standard uncertainties is done in case the final result is numerically determined from the input quantities, for example, the determination of a load spectrum out of time series using rain flow counting. The ISO guide gives no practical procedure for these situations. In the proposed procedure for these situations the standard uncertainty of the final result is determined through Monte Carlo calculations. The calculation of the final result is repeated several times with various values for the input quantities. The values for the input quantities are randomly drawn from a normal distribution with as mean value the measured input value and with as standard deviation the standard uncertainty of the input quantity. The standard deviation of the series of final results is the estimate of the standard uncertainty of the final result.

The input quantities that are expected to be fully (positively) correlated are drawn from their normal distribution with the same generated random numbers. In case input parameters are expected to be uncorrelated, each input parameter is drawn from its normal distribution using different generated random numbers.

B.2 Application for blade load measurements

B.2.1 Calibration uncertainty

B.2.1.1 Determination of the calibration matrix

The bending moments in flatwise direction and in edgewise direction of the blade are measured using a flatwise strain gauge bridge and an edgewise strain gauge bridge. The dependency of the two measurement signals on the flatwise and edgewise bending moments is determined by calibration. The possible crosstalk effect of the edgewise bending moment on the flatwise signal and the possible crosstalk effect of the flatwise bending moment on the edgewise signal are also determined by calibration and corrected during the load measurements.

The calibration is performed by applying various well-known bending moments in flatwise direction only and after that in edgewise direction only. At the same time both bridge signals are measured. The dependencies of the signals on the bending moments are determined by linear regression of the signals and the moments. The offset values that result from the linear regressions are not used. The values for the slopes form the calibration matrix:

$$\begin{bmatrix} s_f^c \\ s_e^c \end{bmatrix} = \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix} \times \begin{bmatrix} M_f^c \\ M_e^c \end{bmatrix} \tag{B.4}$$

where

s_f^c is the signal of the strain-gauge bridge in the flatwise direction (in µV/V);

s_e^c is the signal of the bridge in the edgewise direction (in µV/V);

M_f^c is the flatwise bending moment (in Nm);

M_e^c is the edgewise bending moment (in Nm);

A_i (i = 1 … 4) are the calibration coefficients; the coefficients A_2 and A_3 are caused by crosstalk and are zero in the ideal case.

The values of the calibration coefficients and their associated type A uncertainties (s_{Ai}) are derived by linear regression of the data-points obtained by the calibration.

The type B uncertainties of the calibration coefficients (u_{Ai}) are caused by the type B uncertainties in

- the measured signals ($uS_f{}^c$ and $uS_e{}^c$),
- the measured load (uF_f and uF_e),
- the measured distance between strain gauges and applied load (uL_f and uL_e),
- the direction of the applied force w.r.t. the blade axis ($u\alpha_f$ and $u\alpha_e$), and
- the direction of the applied force w.r.t. the blade cord ($u\theta_f$ and $u\theta_e$).

These uncertainties are estimated by the experimenter for the highest applied calibration load. The type B uncertainty in each of the calibration coefficients is determined in the following way:

$$A_1 = s_f^c / m_f^c = s_f^c / (F_f L_f \cos\alpha_f \cos\theta_f)$$

$$A_2 = s_f^c / m_e^c = s_f^c / (F_e L_e \cos\alpha_e \cos\theta_e)$$

$$A_3 = s_e^c / m_f^c = s_e^c / (F_f L_f \cos\alpha_f \cos\theta_f)$$

$$A_4 = s_e^c / m_e^c = s_e^c / (F_e L_e \cos\alpha_e \cos\theta_e)$$

Assuming no correlation between the type B uncertainties justifies the application of equation (B.2):

$$u_{A1}^2 = u_{S_f^c}^2 \left(\frac{\delta A_1}{\delta S_f^c}\right)^2 + u_{Ff}^2 \left(\frac{\delta A_1}{\delta F_f}\right)^2 + u_{Lf}^2 \left(\frac{\delta A_1}{\delta L_f}\right)^2 + u_{\alpha f}^2 \left(\frac{\delta A_1}{\delta \alpha_f}\right)^2 + u_{\theta f}^2 \left(\frac{\delta A_1}{\delta \theta_f}\right)^2 \tag{B.5}$$

and similar for $u_{A_2}^2$, $u_{A_3}^2$ and $u_{A_4}^2$.

The combined type A and type B uncertainties in the coefficients are calculated by the following equation.

$$u_{cAi} = \sqrt{s_{Ai}^2 + u_{Ai}^2} \;;\; i = 1...4 \tag{B.6}$$

B.2.1.2 Use of the calibration matrix

a) Crosstalk not negligible

The calibration matrix is used for converting the measurement signals into load signals using the inverse of the calibration matrix of B.2.1.1:

$$\begin{bmatrix} M_f \\ M_e \end{bmatrix} = \begin{bmatrix} D_1 & D_2 \\ D_3 & D_4 \end{bmatrix} \times \begin{bmatrix} S_f \\ S_e \end{bmatrix} = \frac{1}{A_1 A_4 - A_2 A_3} \begin{bmatrix} A_4 & -A_2 \\ -A_3 & A_1 \end{bmatrix} \times \begin{bmatrix} S_f \\ S_e \end{bmatrix} \tag{B.7}$$

For simplicity reasons the uncertainties in A_1, A_2, A_3 and A_4 are assumed to be uncorrelated. With this assumption the uncertainties in the D-coefficients can be determined using the values of A and u_{cA} by application of equation (B.2):

$$u_{cD1}^2 = u_{cA1}^2 \left(\frac{\delta D_1}{\delta A_1}\right)^2 + u_{cA2}^2 \left(\frac{\delta D_1}{\delta A_2}\right)^2 + u_{cA3}^2 \left(\frac{\delta D_1}{\delta A_3}\right)^2 + u_{cA4}^2 \left(\frac{\delta D_1}{\delta A_4}\right)^2 \tag{B.8}$$

$$D_1 = \frac{A_4}{A_1 A_4 - A_2 A_3} \rightarrow \frac{\delta D_1}{\delta A_1} = \frac{-A_4^2}{(A_1 A_4 - A_2 A_3)^2} \tag{B.9}$$

and similar for D_2, D_3 and D_4 and their partial derivatives.

The uncertainties in the coefficients D_i are translated to uncertainties in measured loads due to calibration uncertainties ($u_{cal,f}$ and $u_{cal,e}$) by application of equation (B.2):

$$M_f = D_1 \times S_f + D_2 \times S_e \tag{B.10}$$

$$M_e = D_3 \times S_f + D_4 \times S_e \tag{B.11}$$

$$u_{cal,f} = \sqrt{u_{cD1}^2 \times S_f^2 + u_{cD2}^2 \times S_e^2} \tag{B.12}$$

$$u_{cal,e} = \sqrt{u_{cD3}^2 \times S_f^2 + u_{cD4}^2 \times S_e^2} \tag{B.13}$$

This uncertainty is assumed to be fully correlated for all time samples of all 10-min series because all measurement data are treated with the results of one calibration run.

b) Crosstalk negligible

In case the crosstalk is negligible, the use of the calibration matrix is simplified very much. In this case, the relative uncertainty in the measured load due to the calibration uncertainty is equal to the relative uncertainty in the calibration coefficient:

$$u_{cal,f} = M_f \times \frac{u_{cA1}}{A_1} \tag{B.14}$$

$$u_{cal,e} = M_e \times \frac{u_{cA4}}{A_4} \tag{B.15}$$

B.2.2 Time series

The uncertainty in the value of each time sample of the flatwise and the edgewise bending moment consists of an uncertainty due to the applied calibration results ($u_{cal,f}$ and $u_{cal,e}$) and of an uncertainty in the measured signals (u_{Sf} and u_{Se}).

a) Calibration uncertainty

The values of $u_{cal,f}$ and $u_{cal,e}$ are determined per time sample as described in B.2.1.2:

$$u_{cal,f} = \sqrt{u_{cD1}^2 \times S_f^2 + u_{cD2}^2 \times S_e^2}$$

$$u_{cal,e} = \sqrt{u_{cD3}^2 \times S_f^2 + u_{cD4}^2 \times S_e^2}$$

b) Signal uncertainty

The uncertainty in the measured signals originate from signal noise (for example, from electromagnetic interference) and from zero drift (for example, from temperature effects on the strain gauges). In general terms, the signal uncertainty can be written as $u_{Sf} = a \times S_f + b$ in which S_f is the value of the flatwise signal and a and b are coefficients to be estimated by the experimenter using his knowledge about the measurement system. The same is done for u_{Se}. The measurement uncertainties in each time sample of the signals are converted to the associated uncertainty in each time sample of the bending moments by the following equations.

$$u_{sig,f} = \sqrt{D_1^2 \times u_{Sf}^2 + D_2^2 \times u_{Se}^2}$$

$$u_{sig,e} = \sqrt{D_3^2 \times u_{Sf}^2 + D_4^2 \times u_{Se}^2}$$

c) Total uncertainty

The total uncertainty due to the calibration uncertainty and the signal uncertainty per time stamp of the measured flatwise and edgewise bending moment are calculated by the following equations.

$$U_f = \sqrt{u_{cal,f}^2 + u_{sig,f}^2}$$

$$U_e = \sqrt{u_{cal,e}^2 + u_{sig,e}^2}$$

B.2.3 Mean load versus wind speed

The mean flatwise moment and the mean edgewise moment can be measured as a function of wind speed by measuring 10-min averaged values of the flatwise signal, edgewise signal and wind speed. The 10-min averaged flatwise and edgewise signals are converted to 10-min averaged flatwise and edgewise moments using the calibration matrix (see B.2.1.2). The load curves are obtained by binning the two moments against the wind speed.

The uncertainty in the load curves consists of an uncertainty in each bin-averaged moment. These uncertainties are caused by the uncertainties in the calibration, the uncertainty in the measured flatwise and edgewise signal and the uncertainty in the wind speed.

a) Calibration uncertainty

The uncertainty per 10-min averaged load due to the uncertainty in the calibration are determined in the same way as described in B.2.2 but now based on the 10-min averaged values of S_f and S_e instead of each time stamp. Since the calibration uncertainty of the 10-min averaged load values are fully correlated, equation (B.3) is combined with equations (B.12) and (B.13) to determine the uncertainty of the bin-averaged loads:

$$u_{cal,f} = \frac{1}{N}\sum_{i=1}^{N}\left(\sqrt{u_{cD1}^2 \times S_f^2 + u_{cD2}^2 \times S_e^2}\right)_i$$

$$u_{cal,e} = \frac{1}{N}\sum_{i=1}^{N}\left(\sqrt{u_{cD3}^2 \times S_f^2 + u_{cD4}^2 \times S_e^2}\right)_i$$

where N is the number of entries in the bin considered.

b) Signal uncertainty

The uncertainty in each 10-min averaged load due to the signal uncertainties is determined as a type A uncertainty by calculating the standard deviation of the 10-min averaged loads in the regarded bin. The uncertainties in the various 10-min averaged load values due to signal uncertainties are assumed to be uncorrelated. Therefore, the uncertainty in the bin-averaged loads due to the uncertainty in the signals is determined using the standard deviation of the 10-min averaged moments in each bin ($stdev_{Mf}$ and $stdev_{Me}$) and the number of entries (N) in each bin by the application of equation (B.2).

$$u_{sig,f} = stdev_{Mf} / \sqrt{N}$$

$$u_{sig,e} = stdev_{Me} / \sqrt{N}$$

c) Wind speed uncertainty

The uncertainty in the measured wind speed per bin ($u_{v,i}$) is determined as the category B uncertainty of the wind speed in annex D of IEC 61400-12. This uncertainty is translated to the associated uncertainty in the bin-averaged bending moments ($u_{v,f}$ and $u_{v,e}$) using the slope of the preceding part of the load curve:

$$u_{v,f} = u_{v,i} \times \frac{M_{f,i} - M_{f,i-1}}{v_i - v_{i-1}}$$

$$u_{v,e} = u_{v,i} \times \frac{M_{e,i} - M_{e,i-1}}{v_i - v_{i-1}}$$

where i is the index of the regarded bin, starting with the second bin (i = 2).

The values of $u_{v,f(1)}$ and $u_{v,e(1)}$ are set equal to $u_{v,f(2)}$ and $u_{v,e(2)}$ respectively.

d) Total uncertainty

The total uncertainty is calculated per bin for each bin-averaged bending moment using the equations:

$$U_f = \sqrt{u_{cal,f}^2 + u_{sig,f}^2 + u_{v,f}^2}$$

$$U_e = \sqrt{u_{cal,e}^2 + u_{sig,e}^2 + u_{v,e}^2}$$

e) Remark on turbulence intensity

In case the load curves are determined in classes of turbulence intensity, the uncertainty in the turbulence intensity is not taken into account in the uncertainty of the load curves. The turbulence intensity values are reported together with their uncertainties.

B.2.4 Equivalent load range versus wind speed

The equivalent load range of the flatwise and edgewise moments can be determined as a function of wind speed by measuring various 10-min time series of the flatwise signal and of the edgewise signal together with the 10-min averaged wind speed. The 10-min load signals are converted to 10-min time series of the flatwise and edgewise moments using the calibration matrix (see B.2.1.2). By following the rainflow counting technique each 10-min load series is translated into load ranges. The load ranges are condensed into the equivalent load range (R_{eq}) with two chosen parameters: the equivalent number of cycles per 10 min (n_{eq}) and the slope of the material Wöhler curve (1/m). The equivalent load range curves are obtained by binning the values of R_{eq} for the flatwise and for the edgewise load against the wind speed.

The uncertainty in the equivalent load range curves consist of an uncertainty in the bin-averaged equivalent load range in each bin. These uncertainties are caused by the uncertainties in the calibration, the uncertainty in the measured flatwise and edgewise signal and the uncertainty in the wind speed.

a) Calibration uncertainty

The uncertainty per 10-min equivalent load range due to the calibration uncertainty is determined by a Monte Carlo procedure. In this procedure, the calculation of each R_{eq} value is repeated a number of times (for example, 10 times) with modified time series of the loads. The modified time series are obtained in the following way:

$$M_f^*(t) = M_f(t) + Ran \times u_{cal,f}$$

$$M_e^*(t) = M_e(t) + Ran \times u_{cal,e}$$

where

$M_f^*(t)$ and $M_e^*(t)$ are the modified time series;

Ran is a random number, drawn from a normal distribution with an average of 0 and a standard deviation of 1 (N(0,1)) and

$u_{cal,f}$ and $u_{cal,e}$ are the calibration uncertainties given in B.2.2.

The random number Ran is drawn once per time series modification and within 10 min all time samples are modified using the same value of Ran. In this way, for each 10-min time series, a number of modified R_{eq} values (R_{eq}^*) are obtained for the flatwise and for the edgewise load. The standard deviation of these modified R_{eq}^* values is the uncertainty of the R_{eq} value of the regarded 10-min period caused by the calibration uncertainty. Since the calibration uncertainty of the 10-min averaged equivalent load ranges are fully correlated, equation (B.3) is applied to determine the uncertainty of the bin-averaged equivalent load ranges:

$$u_{cal,f} = \frac{1}{N}\sum_{i=1}^{N}(stdev\ R_{eq,f}^*)_i$$

$$u_{cal,e} = \frac{1}{N}\sum_{i=1}^{N}(stdev\ R_{eq,e}^*)_i$$

where N is the number of entries in the bin considered.

b) Signal uncertainty

The uncertainty in each 10-min averaged equivalent load range due to the signal uncertainties is determined as a type A uncertainty by calculating the standard deviation of the 10-min averaged values in the bin considered. The uncertainties in the various 10-min averaged values due to signal uncertainties are assumed to be uncorrelated. Therefore, the uncertainty in the bin-averaged values due to the uncertainty in the signals is determined using the standard deviation of the 10-min averaged values in each bin ($stdev_{\mathrm{Req,f}}$ and $stdev_{\mathrm{Req,e}}$) and the number of entries (N) in each bin by the application of equation (B.2).

$$u_{\mathrm{sig,f}} = stdev_{\mathrm{Req,f}} / \sqrt{N}$$

$$u_{\mathrm{sig,e}} = stdev_{\mathrm{Req,e}} / \sqrt{N}$$

c) Wind speed uncertainty

The uncertainty in the measured wind speed per bin ($u_{\mathrm{v,i}}$) is determined as the type B uncertainty of the wind speed in annex D of IEC 61400-12. This uncertainty is translated to the associated uncertainty in the bin-averaged bending moments ($u_{\mathrm{v,f}}$ and $u_{\mathrm{v,e}}$) using the slope of the preceding part of the R_{eq} curve:

$$u_{\mathrm{v,f}} = u_{\mathrm{v,i}} \times \frac{R_{\mathrm{eq\,f,i}} - R_{\mathrm{eq\,f,i-1}}}{v_{\mathrm{i}} - v_{\mathrm{i-1}}}$$

$$u_{\mathrm{v,e}} = u_{\mathrm{v,i}} \times \frac{R_{\mathrm{eq\,e,i}} - R_{\mathrm{eq\,e,i-1}}}{v_{\mathrm{i}} - v_{\mathrm{i-1}}}$$

where i is the index of the bin considered, starting with the second bin (i = 2).

The values of $u_{\mathrm{v,f(1)}}$ and $u_{\mathrm{v,e(1)}}$ are set equal to $u_{\mathrm{v,f(2)}}$ and $u_{\mathrm{v,e(2)}}$ respectively.

d) Total uncertainty

The total uncertainty is calculated per bin for each bin-averaged equivalent load range using the equations:

$$U_{\mathrm{f}} = \sqrt{u_{\mathrm{cal,f}}^2 + u_{\mathrm{sig,f}}^2 + u_{\mathrm{v,f}}^2}$$

$$U_{\mathrm{e}} = \sqrt{u_{\mathrm{cal,e}}^2 + u_{\mathrm{sig,e}}^2 + u_{\mathrm{v,e}}^2}$$

e) Remark on turbulence intensity

In case the R_{eq} curves are determined in classes of turbulence intensity the uncertainty in the turbulence intensity is not taken into account in the uncertainty of the R_{eq} curves. The turbulence intensity values are reported together with their uncertainties.

B.2.5 Annual load spectrum

An annual load spectrum can be determined for a chosen annual wind speed, a chosen turbulence intensity and a chosen number of operational events (such as grid loss, brake actions). This is done by rainflow counting of selected 10-min time series corresponding to certain wind conditions and corresponding to the operational events and adding of the results using the number of occurrences on a yearly basis.

The final result can be a range-mean matrix or a from-to matrix. The uncertainty in each cell of the matrix is caused by

– the uncertainty in calibration,

– the uncertainty in the signals,

– the uncertainty in the measured wind conditions and

– the mismatch between the wind conditions needed for the calculations and the wind conditions available during the measurements.

The uncertainty in the measured wind conditions and the mismatch of the wind conditions is not taken into account in the uncertainty of the load spectrum because no ready-to-use procedure for this is known.

The uncertainty due to the calibration uncertainty and the signals uncertainty is taken into account by the Monte Carlo approach. The uncertainties in the time series due to the calibration uncertainty are assumed to be fully correlated during the whole measurement campaign. The uncertainties in the time series due to the signal uncertainties are assumed to be fully correlated within each 10-min series and uncorrelated between the various 10-min series. For this reason, the measured time series of all used 10-min are modified in the following way:

$$M_{\mathrm{f}}^{*}(t) = M_{\mathrm{f}}(t) + Ran \times u_{\mathrm{cal,f}} + Ran_{\mathrm{n}} \times u_{\mathrm{sig,f}}$$

$$M_{\mathrm{e}}^{*}(t) = M_{\mathrm{e}}(t) + Ran \times u_{\mathrm{cal,e}} + Ran_{\mathrm{n}} \times u_{\mathrm{sig,e}}$$

where

Ran is a random number used for all time samples of all 10-min series, and

Ran_{n} is a random number used for all time samples of the 10-min series number n.

The random numbers are drawn from a normal distribution with an average of 0 and a standard deviation of 1 ($N(0,1)$). The values of $u_{\mathrm{cal,f}}$, $u_{\mathrm{cal,e}}$, $u_{\mathrm{sig,f}}$ and $u_{\mathrm{sig,e}}$ are obtained per time sample as described in B.2.2.

Using these modified time series the load matrix is calculated again. By repeating this procedure p times with new values for Ran and Ran_{n}, totally p modified load matrices are obtained. The standard uncertainty of each cell of the matrix is obtained by calculating the standard deviation of the p values in each cell.

Annex C
(informative)

Sample presentation of mechanical load measurements and analysis

C.1 General

In annex C, a sample presentation of mechanical load measurements and analysis based on experiments reported in [6] is presented in order to clarify the methodologies described within the present document as well as the minimum report requirements and recommended formats.

Table C.1 – Capture matrix

Normal power production **Wind speed bin size: 1m/s** **Turbulence bin size: 2 %**																			
Time series length	**Number of 10-min recordings**																		
Wind (m/s) ⇒ I (%) ⇓	4*	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	23
<3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-5	2	10	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5-7	5	23	9	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-9	8	30	28	23	16	5	3	1	3	1	0	0	0	0	1	0	0	0	0
9-11	13	45	62	51	45	45	21	15	10	7	8	1	6	2	6	4	0	0	0
11-13	14	74	121	170	125	88	75	52	48	43	18	18	29	29	25	10	2	2	0
13-15	18	89	116	191	200	146	103	77	86	64	46	49	51	50	23	6	2	0	0
15-17	17	70	101	160	147	108	109	65	51	61	49	57	39	18	11	6	2	0	0
17-19	9	29	53	57	48	49	36	29	22	30	34	31	32	8	4	0	0	0	0
19-21	5	16	21	13	15	16	10	9	2	8	9	6	4	2	0	0	0	0	0
21-23	4	1	1	10	6	3	6	1	0	4	1	0	0	0	0	0	0	0	0
23-25	0	1	4	3	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
25-27	1	3	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
27-29	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>29	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Number of turbulence bins with more than three time series	9	10	9	10	8	8	8	6	6	7	6	5	6	4	5	4	0	0	0
Total number	98	393	520	685	605	460	363	250	222	219	165	162	161	109	70	26	6	2	0
* Median value of bin.																			

C.2 Sample record measurements and analysis

The data presentation and analysis for selected records, representing normal operation, standstill, transient or extreme conditions include the following items:

Table C.2 – Record brief statistical description

Record ID: #951008.129 **Date**: 8/10/95 **Time**: 09:14-09:24 **Wind turbine status**: Normal operation					
Measured quantity	**Mean**	**Sdv**	**Min.**	**Max.**	**1 Hz equivalent load**
Wind speed (m/s)	19,21	2,21	11,93	25,63	–
Wind direction (deg)	1,1	6,3	329,0	27,8	–
Air temperature (°C)	18,5	0,2	18,0	19,4	–
Air pressure (hP)	1005,5	0,3	1004,8	1006,3	–
Air density (kg/m^3)	1,20	–	–	–	–
Nacelle yaw position (°)	–7,8	7,3	–19,8	10,3	–
Electrical power (kW)	100,4	6,6	69,3	130,6	–
RPM (generator axle)	1011,5	1,7	1004,3	1021,0	–
Blade root flapwise b.m. (kNm)	17,20	6,68	–6,40	51,71	35,80 (m=12)
Blade root lead lag b.m. (kNm)	7,34	12,27	–26,86	39,03	46,10 (m=12)
Shaft parallel[1)] b.m. (kNm)	–1,79	13,71	–54,58	43,00	56,35 (m=8)
Shaft normal[1)] b.m. (kNm)	0,88	14,24	–37,58	49,10	56,26 (m=8)
Rotor yaw moment (kNm)	2,09	5,92	–26,24	40,21	33,19 (m=8)
Rotor tilt moment (kNm)	–16,48	9,15	–57,05	22,14	40,10 (m=8)
Rotor torque (kNm)	23,62	1,57	15,86	30,59	7,00 (m=8)
Tower base bending N-S[2)] (kNm)	354,42	67,67	87,86	579,88	215,16 (m=4)
Tower base bending E-W[2)] (kNm)	52,45	59,48	–143,15	282,23	186,48 (m=4)
Tower torsion (kNm)	1,98	6,58	–48,34	53,30	37,69 (m=4)

[1)] Denotes the orientation of the sensors on the rotating axis with respect to the master blade.

[2)] Denotes the orientation of the sensors, for example, N-S stands for north-south direction.

C.2.1 Time series presentation

The time series for the selected record include the wind quantities (figure C.1), the wind turbine operational characteristics (figure C.2) and the blade, rotor and tower quantities (figures C.3 and C.4 the first minute of the record is presented).

C.2.2 Azimuthal variation of blade and shaft loads

The azimuthal variation of the blade flapwise and lead lag as well as the shaft bending moments are presented in figure C.5, including the mean, minimum, maximum and standard deviation azimuthal variation.

C.2.3 Spectral analysis

The power density functions of the blade, rotor and tower loads are presented in figure C.6.

C.2.4 Fatigue spectra

The fatigue spectra for the blade, rotor and tower loads, in terms of load ranges with respect to cumulative number of cycles are presented in figure C.7.

C.3 Wind measurement statistics

The statistics of the wind quantities are presented in figure C.8. Turbulence intensity is presented both as a function of mean wind speed and wind direction

C.4 Wind turbine operational magnitude statistics

The statistics of the wind turbine operational quantities, including mean, maximum, minimum and standard deviation, are presented in figure C.9.

C.5 Mechanical load statistics

The statistics of the measured mechanical loads, including mean, maximum, minimum and standard deviation, are presented in figures C.10 to C.12.

C.6 Fatigue load statistics

The statistics of the fatigue loads, in terms of 1 Hz equivalent loads calculated for two S-N curve slopes representative for each wind turbine component, are presented in figures C.12 to C.15.

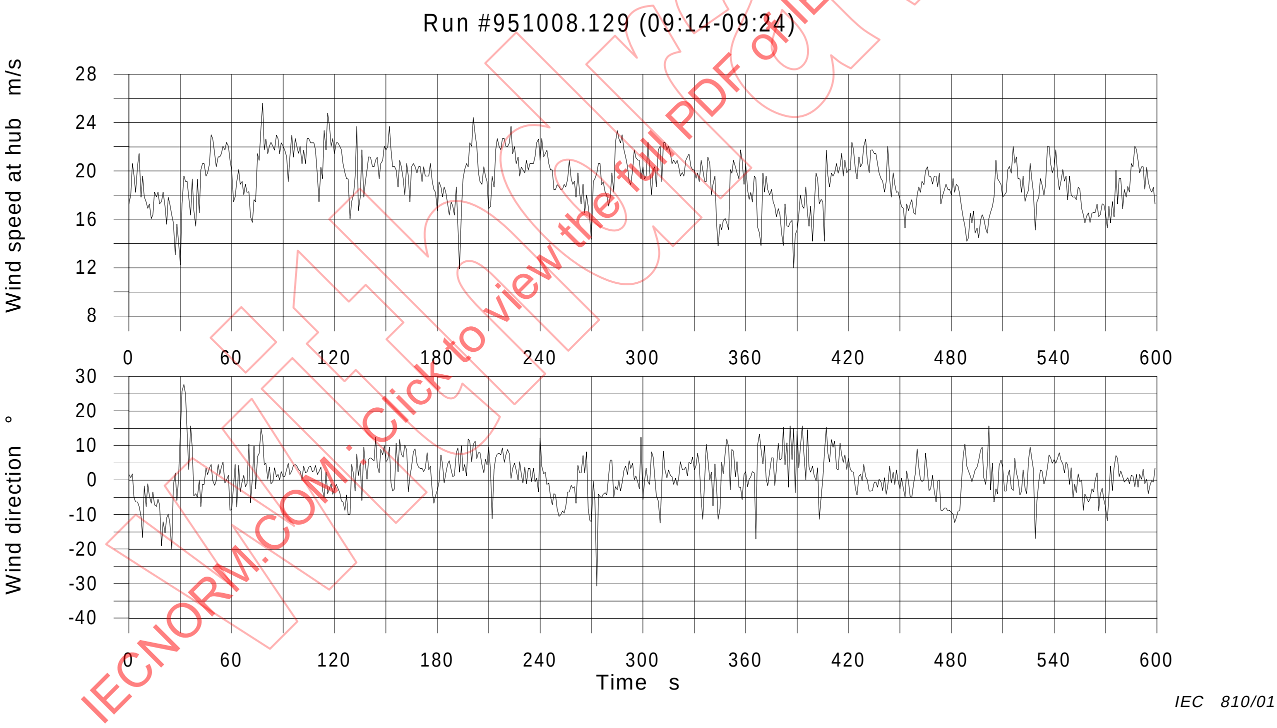


Figure C.1 – Meteorological quantities record time series

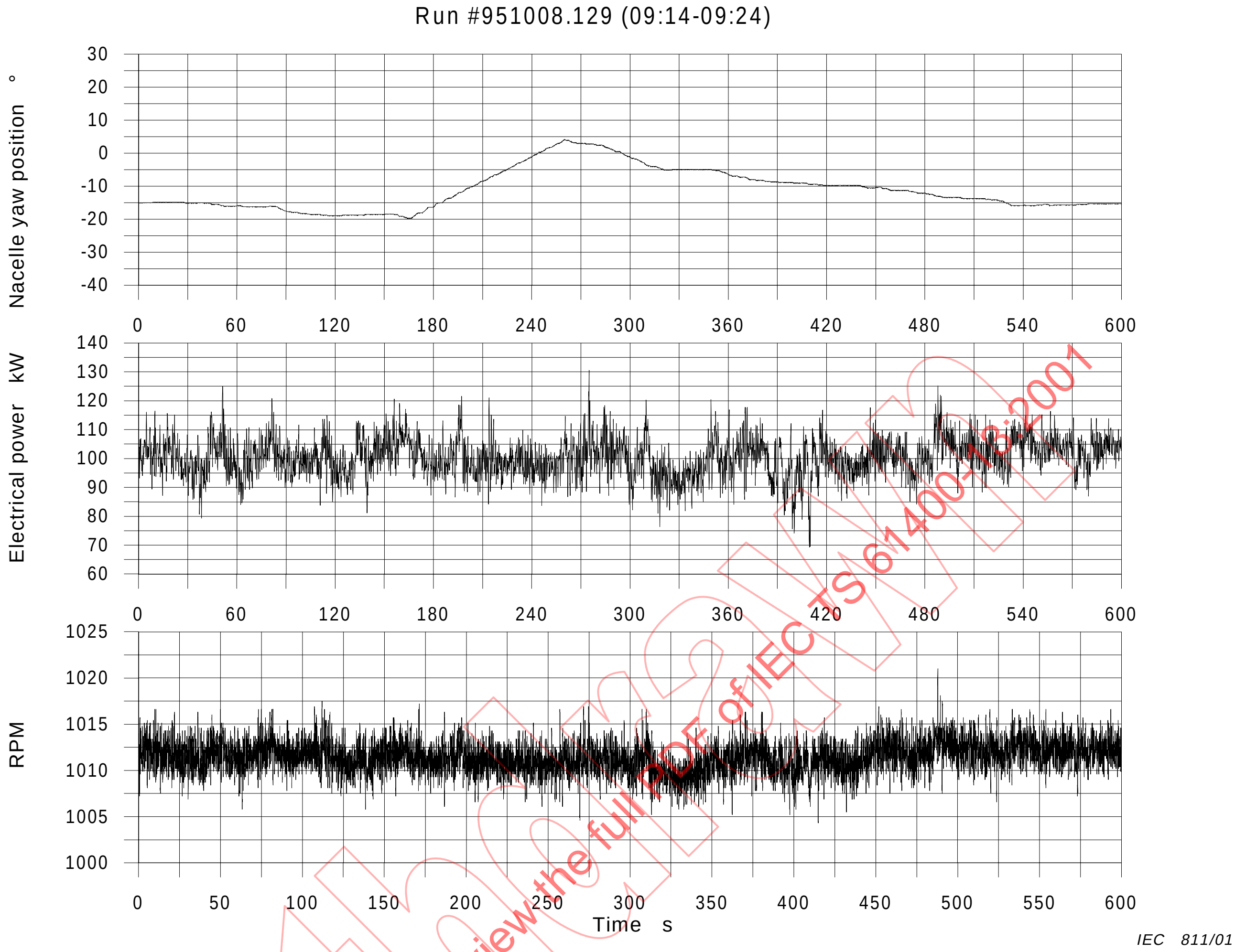


Figure C.2 – Wind turbine operational quantities record time series

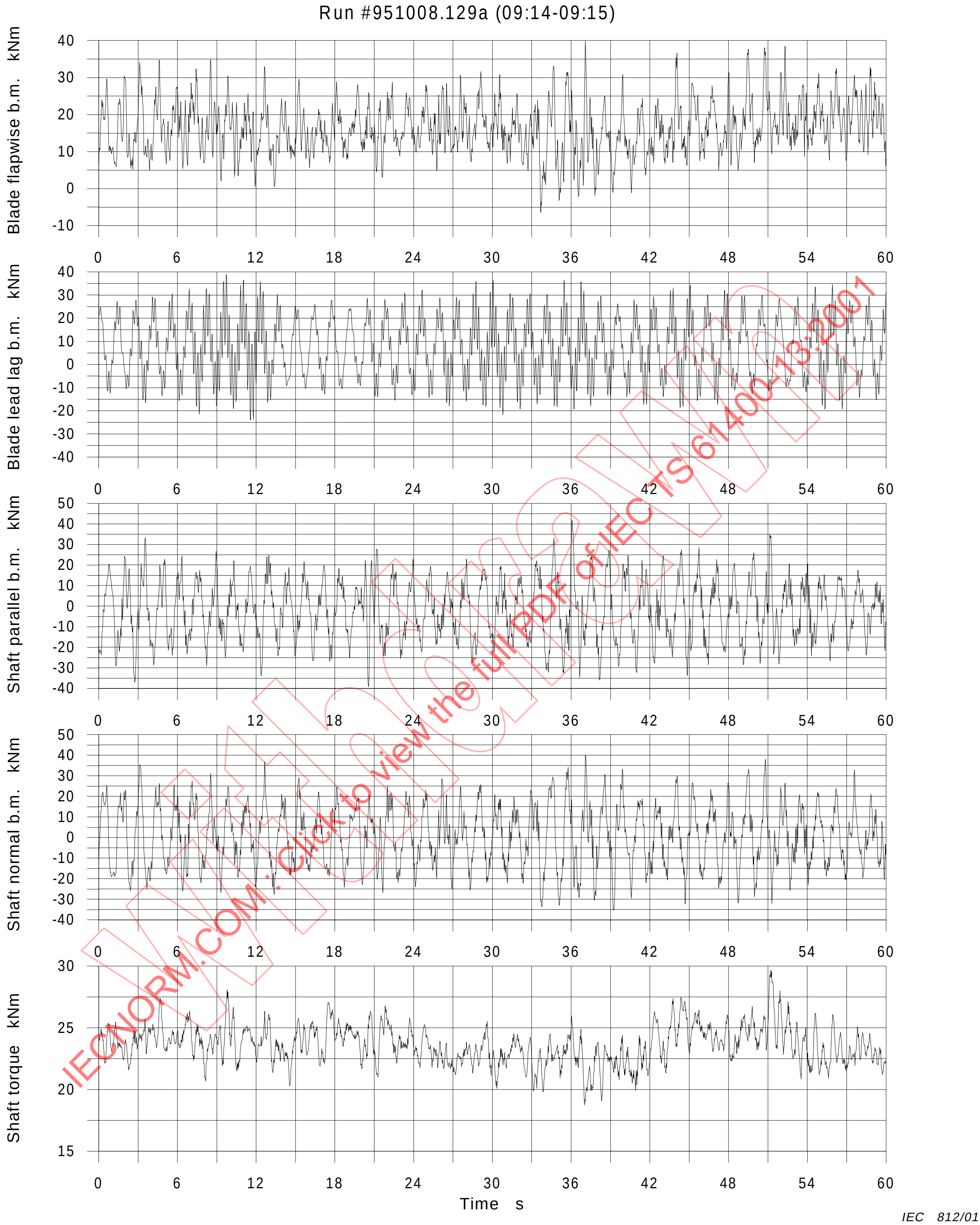


Figure C.3 – Wind turbine mechanical load time series (first minute of record)

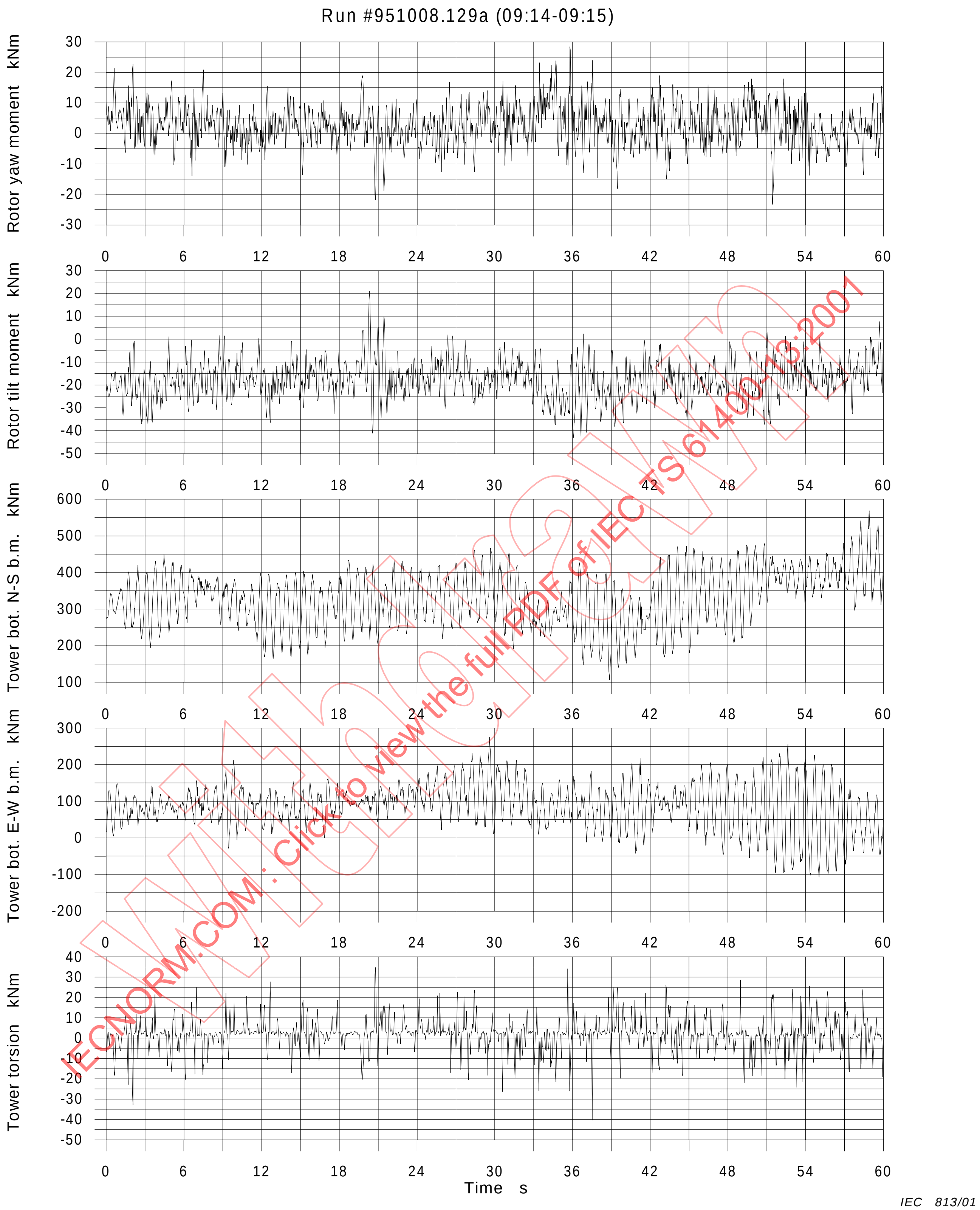


Figure C.4 – Wind turbine mechanical load time series (first minute of record)

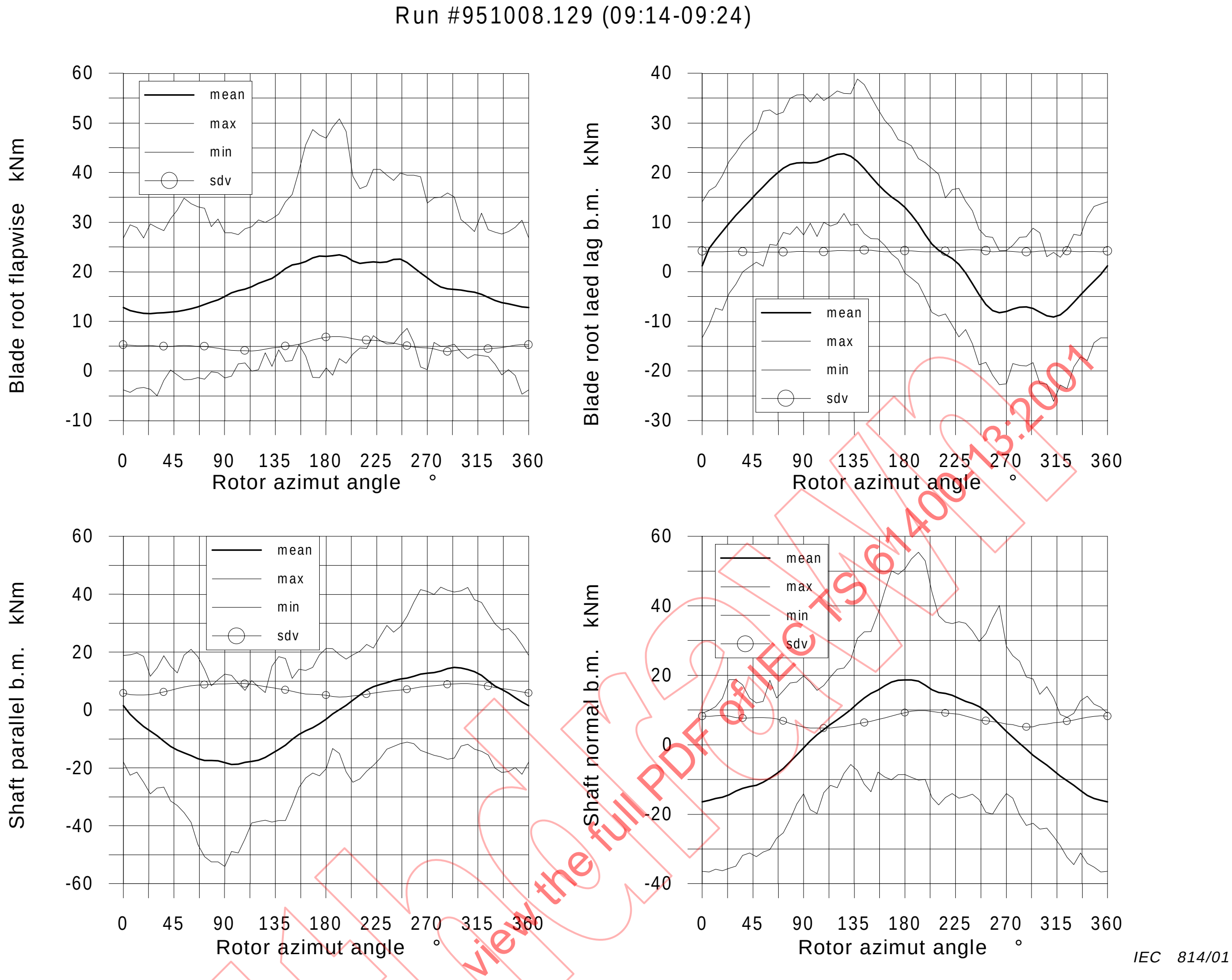


Figure C.5 – Azimuthal variation of blade and shaft loads

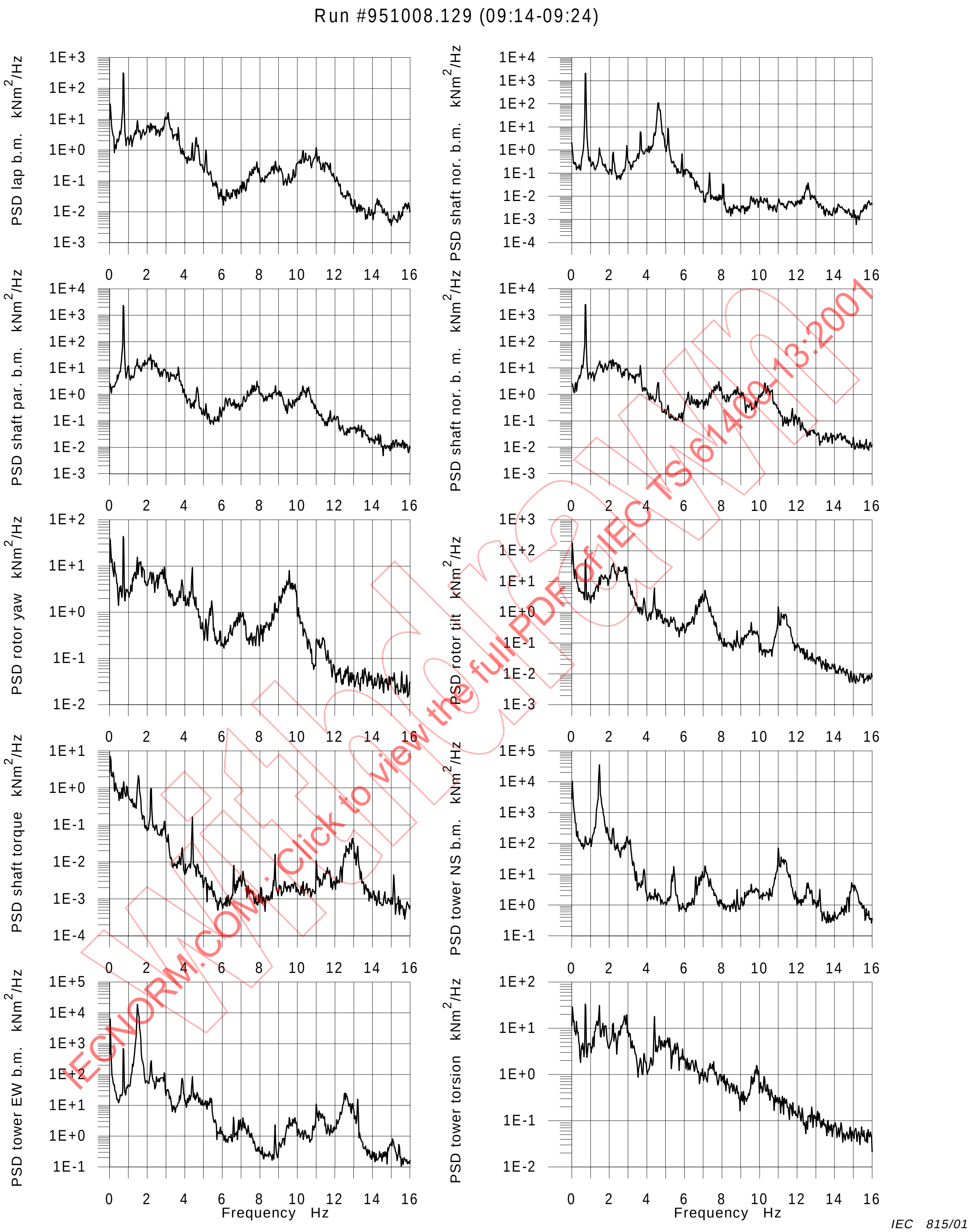


Figure C.6 – Frequency spectral density functions for blade, rotor and tower loads

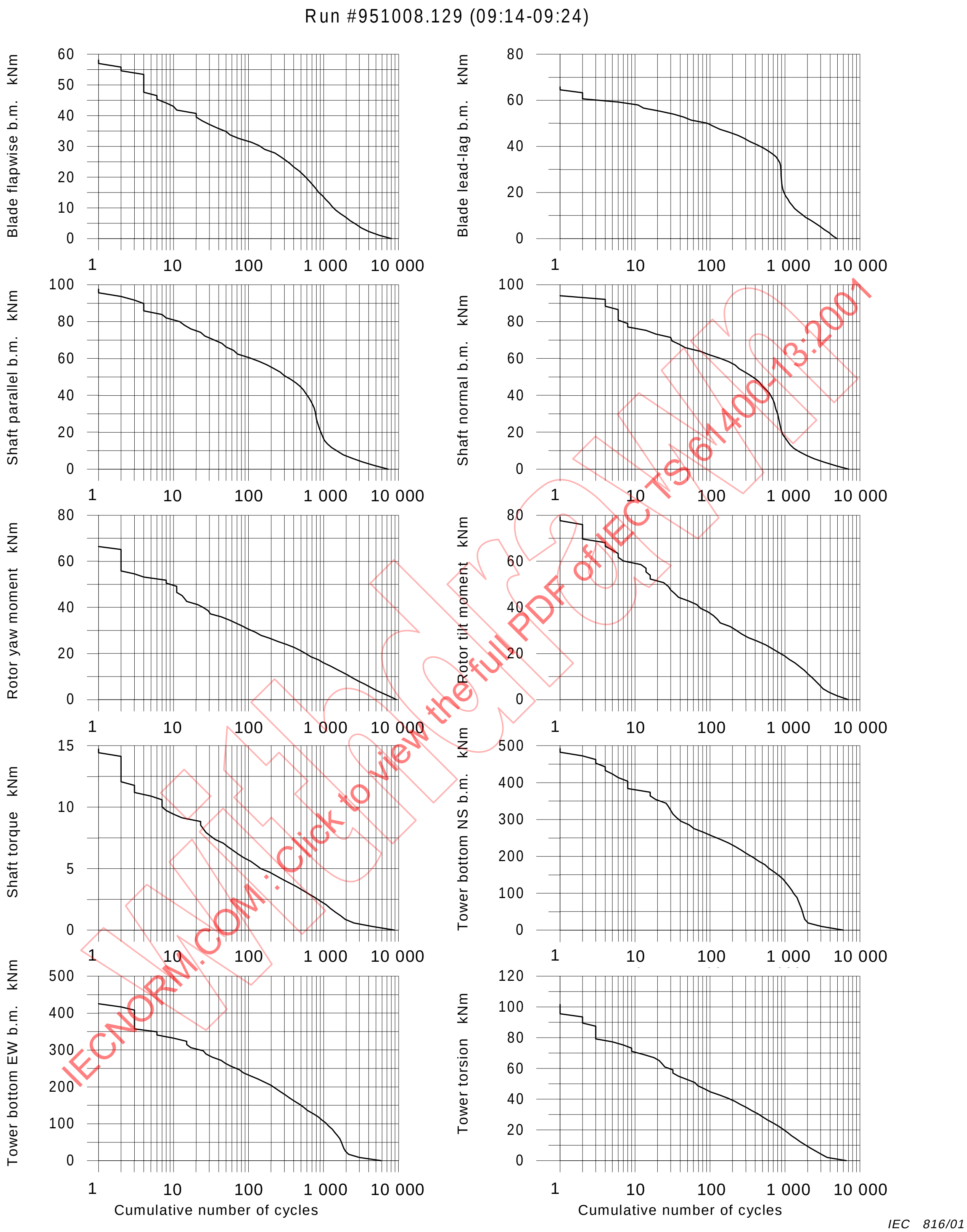


Figure C.7 – Fatigue spectra for blade, rotor and tower loads