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TECHNICAL SPECIFICATION

Marine energy – Wave, tidal and other water current converters –
Part 3: Measurement of mechanical loads

IEC TS 62600-3:2020-05(en)

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Marine energy – Wave, tidal and other water current converters – Part 3: Measurement of mechanical loads

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Part 3: Measurement of mechanical loads

FOREWORD

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

IEC TS 62600-3, which is a Technical Specification, has been prepared by IEC technical committee 114: Marine energy – Wave, tidal and other water current converters.

The text of this Technical Specification is based on the following documents:

Enquiry draft	Report on voting
114/326/DTS	114/336A/RVDTS

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 document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62600 series, published under the general title *Marine energy – Wave, tidal and other water current converters*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

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- withdrawn,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

INTRODUCTION

This part of IEC 62600 outlines specifications for the full-scale mechanical loads measurement on hydrodynamic marine energy converters (MECs). It is directed at a technology readiness level (TRL) of 7 to 9, meaning the last prototype or the first production device. This document also outlines the demands for full-scale structural testing of rotor blades as well as the interpretation and evaluation of test results.

In the process of structural design of marine energy converters, thorough understanding and accurate quantification of the loading is of utmost importance. In the design stage, loads can be predicted with simulation models and codes. However, such models have their modelling restrictions and uncertainties, and they always need to be validated by measurement.

Mechanical load measurements can be used both as the basis for design and as the basis for certification. The design of marine energy converters is covered by IEC 62600-2: Marine Energy – Wave, tidal and other water current converters – Part 2: Design requirements for marine energy systems.

This document is aimed at the test institute, the marine energy converter manufacturer and the certifying body and defines the requirements for mechanical loads tests resulting in consistent and reproducible test results.

There exists a large variety of marine energy converter working principles. This document aims to cover most hydrodynamic marine energy converter working principles. Therefore, generalised tests are presented at the level of the common subsystems. For Tidal Energy Converters (TECs) and for other water current converters, the most common working principle is a turbine comprising blades connected to a rotor shaft. Therefore, detailed tests are specified for this working principle. For marine energy converter working principles that do not fit partly or completely in the scope of this document, the technology qualification process is introduced. Through the technology qualification process, the user can adapt the test programme to their specific marine energy converter.

This document is comparable to the international wind standards IEC 61400-13: Wind turbines – Part 13: Measurement of mechanical loads and IEC 61400-23: Wind turbines – Part 23: Full-scale structural testing of rotor blades. Since testing laboratories and certification bodies already have experience with these wind standards, it is convenient to adapt the same methods where possible.

There is not much published experience with offshore mechanical load measurement on marine energy converters. This document is a first step towards a future International Standard which can be used as part of a type certification process of marine energy converters. First, experience should be gained with offshore mechanical load measurement and with the application of this document.

Compliance with this document does not relieve any person, organization, or corporation from the responsibility of observing other applicable regulations.

MARINE ENERGY – WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS –

Part 3: Measurement of mechanical loads

1 Scope

1.1 General

This part of IEC 62600 describes the measurement of mechanical loads on hydrodynamic marine energy converters such as wave, tidal and other water current converters (including river current converters) for the purpose of load simulation model validation and certification. This document contains the requirements and recommendations for the measurement of mechanical loads for such activities as site selection, measurand selection, data acquisition, calibration, data verification, measurement load cases, capture matrix, post-processing, uncertainty determination and reporting.

Informative annexes are also provided to improve understanding of testing methods. The methods described in this document can also be used for mechanical loads measurements for other purposes such as obtaining a measured statistical representation of loads, direct measurements of the design loads, safety and function testing, or measurement of subsystem or component structural loads.

Through a technology qualification process, the test requirements can be adapted to the specific marine energy converter.

This document also defines the requirements for full-scale structural testing of subsystems or parts with a special focus on full-scale structural testing of marine energy converter rotor blades and for the interpretation and evaluation of achieved test results. This document focuses on aspects of testing related to an evaluation of the structural integrity of the blade. The purpose of the tests is to confirm to an acceptable level of probability that the whole installed production of a blade type fulfils the design assumptions.

1.2 Subdivision of marine energy converter types

There is a wide variety of marine energy converter types, especially concerning wave energy converters (WECs). For tidal energy converters and other current energy converters (CECs) the working principle of a turbine comprising blades connected to a rotor shaft, is common, whether seabed mounted or mounted to floating structures. However, there are also other types of tidal energy converters under development without blades connected to a rotor shaft and there are wave energy converters under development with blades connected to a rotor shaft. This document aims to cover all types of hydrodynamic marine energy converters, being wave energy converters (WECs) and current energy converters (CECs). Therefore, this document provides requirements and recommendations for all wave energy converters and current energy converters. For wave energy converters and current energy converters with blades connected to a rotor shaft, the requirements are specified in more detail, since in this case there is more knowledge about the technical components of the device.

For all wave and current energy converters a subdivision can be made between seabed (or shore) mounted devices (see Figure 1) and floating devices (see Figure 2). The seabed can also be a riverbed and the shore can also be a pier, a bridge girder, a canal lock gate or another artificial construction. The seabed (or shore) mounted devices generally consist of the following subsystems:

- prime mover;

- power take-off (PTO);
- control;
- foundation and/or substructure.

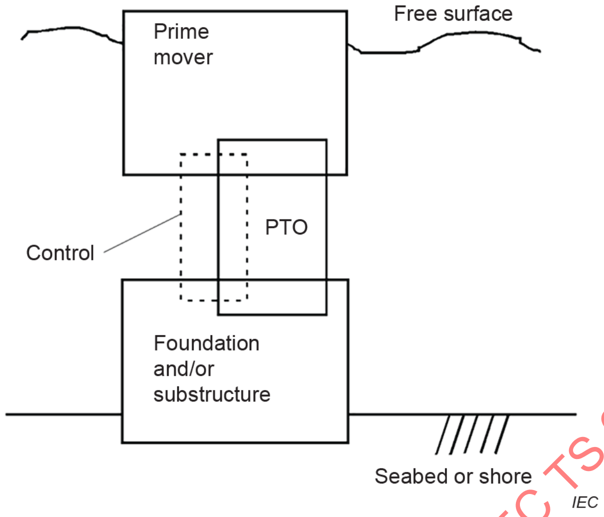

Figure 1 – General scheme of marine energy converters fixed to the seabed or shore

There can be marine energy converter types that do not fit in this characterization like the magneto hydrodynamic device (MHD), where the seawater itself is the prime mover. For such a device the scheme can be reduced to only “foundation and/or substructure”, “power take-off” and “control”. At the oscillating water column device (OWC), air is used to transfer power from the moving seawater to the turbine. Here the air turbine is the prime mover.

Figure 2 gives a scheme for floating marine energy converter working principles. The floating marine energy converters generally consist of the following subsystems:

- prime mover;
- power take-off (PTO);
- control;
- floating device;
- mooring system.

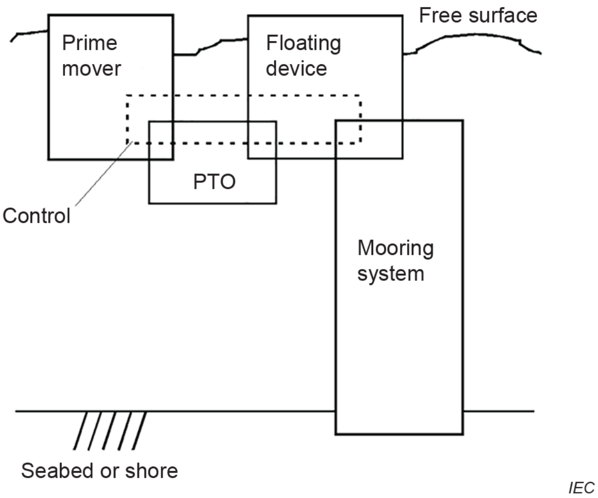

Figure 2 – General scheme of floating marine energy converters moored to the seabed or shore

Other configurations of the subsystems in these figures are also possible. For example, for wave energy converters the power take-off and prime mover can be inside the floating device. Also, a marine energy converter can be composed from more than one subsystem of any kind. The subsystems can also be connected in series, such as alternating series of prime movers and power take-offs, or in parallel. The floating device can also be moored above the seabed but below the free surface.

Special requirements are provided for marine energy converters with one or more blades connected at a single end to a rotor shaft. The rotor forms the prime mover of the marine energy converter. The rotor can rotate with respect to a substructure. The power take-off connects the rotor to the substructure and houses an energy conversion from mechanical power to electrical power or some other form of transportable power such as hydraulic power. This is also called the drive train. The power take-off can be housed in a nacelle. The substructure connects the power take-off to the foundation fixed to the seabed or shore (see Figure 3). A control subsystem can be applied to control critical functions like rotor speed, rotor torque and rotor braking.

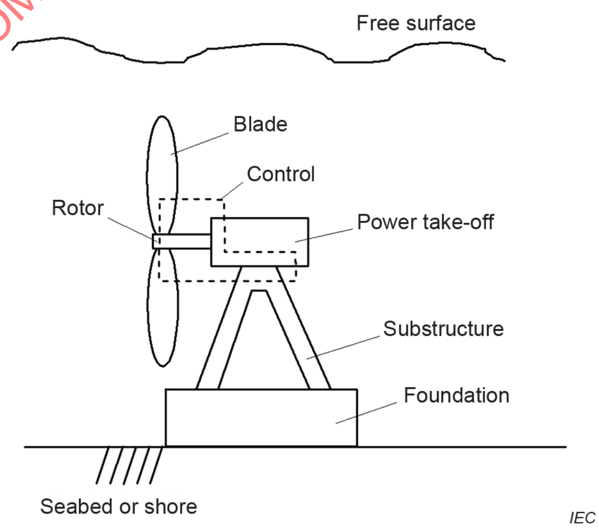

Figure 3 – Marine energy converter with blades connected to a rotor shaft supported by a fixed substructure

There are also optional mechanical components in a control subsystem for example:

- mechanism to allow yawing of the rotor towards the direction of the current (e.g. for the ebb and flood current direction);
- mechanism to allow pitching of the rotor blades for example to optimise power production, to shed loads or to adjust to the direction of the current.

The rotor and power take-off can also be supported by a floating device which is connected to the seabed (or shore) by a mooring system (see Figure 4).

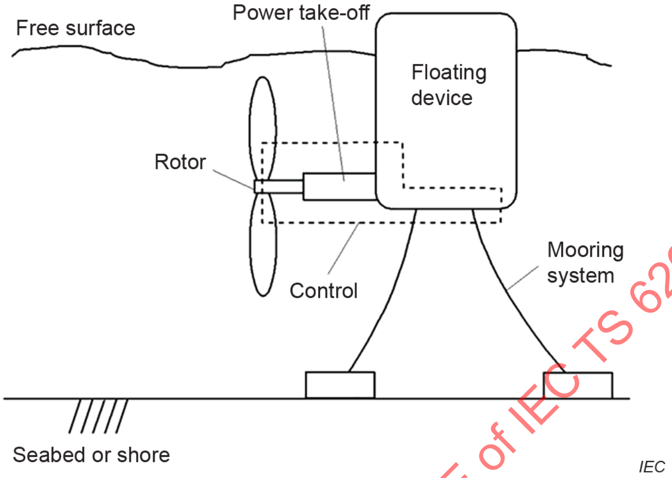

Figure 4 – Marine energy converter with blades connected to a rotor shaft supported by a floating device

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 62600-1, *Marine Energy – Wave, tidal and other water current converters – Part 1: Terminology*

IEC TS 62600-2:2019, *Marine energy – Wave, tidal and other water current converters – Part 2: Marine energy systems – Design requirements*

IEC TS 62600-10, *Marine Energy – Wave, tidal and other water current converters – Part 10: Assessment of mooring system for marine energy converters (MECs)*

IEC TS 62600-100, *Marine Energy – Wave, tidal and other water current converters – Part 100: Electricity producing wave energy converters – Power performance assessment*

IEC TS 62600-200, *Marine energy – Wave, tidal and other water current converters – Part 200: Electricity producing tidal energy converters – Power performance assessment*

IEC TS 62600-300, *Marine energy – Wave, tidal and other water current converters – Part 300: Electricity producing river energy converters – Power performance assessment*

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 62600-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
capture matrix
tabular description of the measurand time series as a function of relevant meteorological and oceanographic parameters

4 Symbols, units and abbreviated terms

4.1 Symbols

B	Number of blades	
C	Constant used in S-N curve formulation	
f	Frequency	[Hz]
f_c	Filter cut off frequency	[Hz]
f_s	Sampling frequency	[Hz]
F	Force	[N]
F_a	Blade flatwise shear force (chordwise coordinates)	[N]
F_b	Blade edgewise shear force (chordwise coordinates)	[N]
F_c	Blade spanwise (tensile) force (chordwise coordinates)	[N]
F_x	Blade flapwise shear force (rotor coordinates)	[N]
F_y	Blade lead-lag shear force (rotor coordinates)	[N]
F_z	Blade spanwise (tensile) force (rotor coordinates)	[N]
H_r	Reduction factor	
i	Index for current speed bin	
j	Index for number of data sets in the i^{th} current speed bin	
L	Number of blades instrumented for blade root bending moments	
m	Slope of S-N curve	
M_a	Blade edgewise bending moment (chordwise coordinates)	[Nm]
M_b	Blade flatwise bending moment (chordwise coordinates)	[Nm]
M_{be}	Blade root edgewise bending moment	[Nm]
M_{bf}	Blade root flatwise bending moment	[Nm]
M_{bi}	Blade root in-plane bending moment	[Nm]
M_c	Blade torsion moment	[Nm]
M_{cl}	Base of tubular column lateral moment	[Nm]
M_{cn}	Base of tubular column normal moment	[Nm]

M_r	Rotor torque	[Nm]
M_s	Blade main shaft torque	[Nm]
M_{tilt}	Rotor tilt moment	[Nm]
M_x	Blade lead-lag bending moment	[Nm]
M_y	Blade flapwise bending moment	[Nm]
M_{yaw}	Rotor yaw moment	[Nm]
M_z	Blade torsion moment (rotor coordinates)	[Nm]
n_{ft}	Number of cycles fatigue test	
n_i	Number of cycles in the ith class of the fatigue load spectrum	
n_0	number of calculated cycles for the design service life	
N	number of cycles to failure at load range level S	
N_i	Number of 10-min data sets in bin i	
P	Power output of the MEC	[W]
P_r	Rated power	[W]
r	Rotor radius	[m]
r_g	Radius of strain gauge location	[m]
R_{eq}	1 Hz 10-min equivalent load	[Nm]
R_i	Load of the i^{th} range bin of the fatigue load spectrum	[Nm]
S	Load range	[Nm, N]
v_i	Bin averaged current speed in current speed bin i	[m/s]
$v_{i,j}$	10-min averaged current speed of data set j in current speed bin i	[m/s]
x_b, y_b, z_b	Blade coordinates (see Figure B.1)	
x_h, y_h, z_h	Hub coordinates (see Figure B.2)	
x_i	Bin averaged variable in question in current speed bin i	
$x_{i,j}$	10-min averaged variable of data set j in current speed bin i	
x_n, y_n, z_n	Nacelle coordinates (see Figure B.3)	
x_t, y_t, z_t	Tubular column coordinates (see Figure B.4)	

4.2 Greek symbols

γ	Partial factor or test load factor	
γ_{ef}	Test load factor	
γ_f	Partial factor for loads	
γ_m	Material factor	
γ_{m2}	Material factor for variations in manufacturing process	
γ_{m3}	Material factor for environmental factors	
η	Efficiency of the components between point of main shaft torque measurement and point of power measurement	[%]
σ	Standard deviation	

σ_{xi}	Standard deviation of the mean in current speed bin i	
φ_F	Angle for yaw misalignment	[°]
Ω	Rotor speed	[rad/s]

4.3 Subscripts

df	Design load: fatigue
du	Design load: static
ef	Uncertainty in fatigue formulation of test load
f	Load
lf	Environmental effects: fatigue
lu	Environmental effects: static
sf	Blade to blade variation: fatigue test load
su	Blade to blade variation: static test load
target	Target loading conditions
test	Test loading conditions

4.4 Abbreviated terms

DAS	Data acquisition system
DEL	Damage equivalent load
DLC	Design load case
FBG	Fibre Bragg grating optical strain sensor
MLC	Measurement load case
PSD	Power spectral density
TI	Turbulence intensity

5 General

5.1 Document structure

This document is structured to follow the general process for conducting mechanical loads tests:

- Clause 6 contains the requirements for the test site, measurement load cases and the quantities to be measured;
- Clause 7 contains the requirements on the instrumentation to be used;
- Clause 8 contains the requirements for the calibration factors;
- Clause 9 contains the recommendations for the data verification (both verification of the calibrations and verifications to be performed throughout the campaign);
- Clause 10 contains the requirements for the processing of the measured data;
- Clause 11 contains the requirements for uncertainty estimation, and
- Clause 12 contains the requirements for the reporting of the results.

The document also contains a normative annex on rotor blade testing for MECs with blades connected to a rotor shaft (Annex A).

In addition to the normative clauses above, the document also contains informative annexes for the following subjects:

- Example coordinate systems for MECs with blades connected to a rotor shaft;

- Recommendations for design and testing of MECs with respect to ice loading and ice accretion;
- Offshore load measurement;
- Uncertainty analysis;
- Load model validation;
- Formulation of test load for rotor blade testing;
- Difference between design and test load conditions for rotor blade testing;
- Determination of number of load cycles for fatigue tests of rotor blades.

5.2 Safety during testing

Certain measurement load cases (MLCs) involve deliberate operation of the MEC in extreme and/or emergency fault conditions (for example, grid loss). As the purpose of the tests and measurements is to verify loads on a prototype MEC, it shall not be assumed that the MEC 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. Preferably, such tests should not be carried out with personnel inside or on the MEC. If possible, such tests should be initiated and observed from a safe position, usually at a safe distance with the MEC downstream or down wave (considering current or dominant wave direction) of the observer. Through the technology qualification process of 5.3, the test requirements can be adapted to the specific MEC. All tests and test procedures shall be agreed with the MEC manufacturer before implementation to ensure that the MEC integrity, and hence that personnel safety, is not compromised. Requirements from existing applicable safety standards shall be followed.

5.3 Technology qualification

If the developer does not follow the requirements in this document, then a technology qualification process should outline how the risks associated with not following the requirements, have been mitigated. For technology qualification see IEC TS 62600-2.

It should be noted that in addition to the tests outlined in this document, which are aligned with the design load cases of IEC TS 62600-2, there may be additional tests which are identified during a technology qualification process. For example, if the device incorporates novel elements these elements may need to be tested to prove functionality can be achieved (see 6.3). These tests should follow the general properties outlined in this document.

NOTE A new Technical Specification for technology qualification is being developed for marine energy (IEC TS 62600-4).

5.4 Load measurement

Generally material stresses cannot be measured directly but are measured as strains at or in the material. In the material there is a three-dimensional set of tension (or compression) and shear stresses which is called a stress tensor. From the measured strains, the stresses can be deduced and from the stresses the loading can be deduced. Therefore, this process is referred to as load measurement. For ductile metals the Von Mises yield criterion can be used to reduce the complex tensor to a single representative stress.

6 Test requirements

6.1 General

In Clause 6 the requirements for the tests are described. These include requirements for:

- the test site;
- the MLCs and the amount of data required for each;

- the quantities to be measured;
- changes in the MEC configuration.

Through the technology qualification process of 5.3, the test requirements can be adapted to the specific MEC.

6.2 Test site requirements all WEC and CEC

The bathymetry and the metocean conditions should be capable of fulfilling the requirements of IEC TS 62600-100, IEC TS 62600-200 or IEC TS 62600-300 as applicable for the MEC. A test site assessment should be completed according to the applicable standard. If the test site does not meet the requirements of this standard, a site survey should be performed. It should be noted that high turbulence and high wave energy flux is better for a mechanical loads test due to the necessary excitation of all WEC or CEC dynamics. The test site should reach at least the rated power that the MEC is designed for.

In general, the accuracy requirements for the metocean conditions for a mechanical loads test are not as stringent as for power performance testing. However, if no site survey is performed in a complex bathymetry where large correction factors can be expected there is increased risk that the test data may not be suitable for model validation.

6.3 Subsystem or structural component laboratory load testing

Separate full-scale testing of subsystems or structural components in a laboratory should be considered when:

- a subsystem (or structural component) is used in a different environment than which it is certified for or tested for, or the subsystem (or structural component) is used in a different way than it is certified for or tested for;
- the loading of the subsystem or structural component is not well understood;
- the subsystem or structural component is constructed from anisotropic or layered materials in which the stresses are not fully predictable, or in which the production process has influence on for example the fatigue strength or durability in seawater (for example rotor blades);
- the complex nature of the subsystem or structural component makes it difficult to predict the stresses in the part (for example a gearbox with a shaft under stochastic multi directional loading and complex internal dynamic effects);
- The calculated reserve against fatigue failure is low (see Annex G).

For WECs and CECs with blades connected to a rotor shaft, the rotor blades shall be tested as specified in Annex A.

Through the technology qualification process of 5.3, the necessity of full-scale testing of subsystems or structural components can be identified for the specific MEC.

6.4 Measurement load cases all WEC and CEC

6.4.1 General

6.4 provides the minimum required MLCs needed for proper model validation. Where applicable the MLCs are defined in relation to the DLCs, described in IEC TS 62600-2: 2019.

The MLCs define the main external conditions and the operational states of the MEC during the measurements. The external conditions include oceanographic and meteorological quantities. The operating states depend on the MEC configuration and shall be specified for each particular case.

Due to the stochastic character of the external conditions, measurements of some MLCs shall be repeated in order to reduce the statistical uncertainty. The minimum number of measurements at each MLC is specified.

The measured time histories are classified in two ways: one considering steady-state operation and one considering transient events. During the steady state operation time series, the MEC should be in a stable condition. For a TEC it can take 5 min or less from start-up and for a WEC it can take 20 min or more. The averaging period should be as in IEC TS 62600-100, IEC TS 62600-200 or IEC TS 62600-300 as applicable.

Table 1, Table 2 and Table 3 show the minimum MLCs that shall be recorded. The MLCs defined in the tables may not be sufficient. Additional MLCs may be necessary depending on the MEC concept, control strategy, and safety strategy. The MLCs should demonstrate that the MEC can reach the safety and reliability levels that resulted from the model simulation calculations. Therefore, the simulation model should be validated with the load measurements, and the simulation calculations should be extrapolated to determine the ultimate limit state and the fatigue limit state. Care should be taken that the simulation calculations are also extrapolated to the natural or critical frequencies of all the subsystems.

There is the following hierarchy in the measurement load cases:

a) Human safety and station keeping (see IEC TS 62600-2:2019, 5.5);

b) Normal design category (see IEC TS 62600-2:2019, 7.3.3);

c) Abnormal and extreme design category (see IEC TS 62600-2:2019, 7.3.3);

MLCs that are required by local, state, regional, national or federal regulations are mandatory.

Through the technology qualification process of 5.3, the MLCs can be adapted to the specific MEC.

6.4.2 MLCs during steady-state operation

6.4.2.1 General

In the steady state operation, there are in general two operating states: power production and parked or idling (see Table 1). Important are combinations of currents and waves that can induce excitation of the natural frequencies or special dynamics of the MEC. For the case that the control system is programmed to avoid these excitations, see 6.4.5.

6.4.2.2 Power production

During power production, measurements should be performed according to the criteria of IEC TS 62600-100, IEC TS 62600-200 or IEC TS 62600-300 depending on the application of the MEC.

6.4.2.3 Parked

For MECs that have a parked condition, the loads on the parked MEC shall be measured (see Table 1). It is recommended that measurements be performed at water speed and/or wave energy flux as high as possible at the site. The combination of currents and waves that apply the highest loads on the MEC should be aimed for. The same method applies for MECs without a parked condition.

Table 1 – MLCs during steady-state operation

MLC number	MLC	DLCs IEC TS 62600-2:2019 Table 7 and Table 8	Remarks
1.1	Power production	1)	In this mode of operation, the MEC is running and connected to the grid
1.2	Parked	6)	When the MEC is parked, the prime mover may be either in a standstill or idling

6.4.3 MLCs during transient events

6.4.3.1 General

These MLCs include all events resulting in loads on the MEC during the transients from the one operating state to the other. For example, from the operating state standstill or idling to power production and vice versa (see Table 2). Other transients between operating states than the ones that are given in 6.4.3.2, 6.4.3.3, 6.4.3.4 and 6.4.3.5 are possible depending on the working principle of the MEC and the settings of the control system.

6.4.3.2 Start-up

The normal start-up of the MEC should be performed at around 10 % of rated power and at rated power. If the MEC operates at more than one fixed rotational or translational speed, start-up at the different speeds should be evaluated also.

6.4.3.3 Normal shutdown

This design situation includes all events resulting in loads on a MEC during the normal transient caused by going from power production to a parked condition. The normal shutdown should be performed at around 10 % of rated power and at rated power.

6.4.3.4 Emergency shutdown

The loads during an emergency shutdown shall be considered. This shutdown should be performed at rated power.

6.4.3.5 Grid failure

The loads during a grid failure shall be considered. This MLC should be performed while the MEC is producing rated power, by disconnecting the MEC from the grid resulting in a shutdown.

Table 2 – Measurement of transient load cases

MLC number	MLC	DLCs IEC TS 62600-2:2019 Table 7 and Table 8	Target conditions
2.1	Start-up	3)	Around 10 % of rated power and rated power
2.2	Normal shutdown	4)	Around 10 % of rated power and rated power
2.3	Emergency shutdown (by pushbutton)	5)	Rated power
2.4	Grid failure		Rated power

6.4.4 MLCs for dynamic characterization

Table 3 provides the measurement load cases that are recommended for the dynamic characterization of the MEC frequencies. The table also provides the targeted frequencies for each MLC. Artificial excitation can be an important first test for dynamic characterization under controlled circumstances, for example in a sheltered harbour.

Table 3 – MLCs for dynamic characterization

MLC number	Measurement load case	DLCs IEC TS 62600-2:2019 Table 7 and Table 8	Target frequencies	Comment
3.1	Power production	1)	Prime mover, PTO and substructure frequencies[c]	Normal operation with relatively steady power production
3.2	Parked[a]	6)	Prime mover and substructure frequencies[c]	MEC is parked (standstill or idling)
3.3	Emergency stop	5)	Prime mover, PTO and substructure frequencies[c]	Emergency stop from rated power
3.4	Artificial excitation[b]		Prime mover and substructure frequencies[c]	The MEC will be brought in excitation by an artificial force under controlled circumstances

[a] High enough water speed and/or wave energy flux to obtain sufficient excitation, this will be MEC specific.

[b] Low enough water speed and wave energy flux to not have the excitation affected by other hydrodynamic loads. Testing may be done in a sheltered harbour, for example a decay test for a WEC and a pulling test for a CEC.

[c] Depending on the WEC or CEC configuration, the target frequencies can also be foundation frequencies, floating device frequencies or mooring system frequencies.

6.4.5 MLC for abnormal operating condition

In the case of an abnormal operating condition (according to IEC TS 62600-2), such as a control system failure, the MEC's electrical, mechanical, and control system shall transition to a safe condition or state that is safe for humans to service. Therefore, the structural integrity should be safeguarded as well as the station keeping. In this MLC, the control system shall be switched off at rated power. There should be no dangerous moving components, vibrations or accelerations when the water speed and/or wave height is deemed acceptable for service personnel to engage with the MEC.

6.4.6 Capture matrices

6.4.6.1 General

Capture matrices are used to organize the measured time series. The capture matrices have two objectives: they are used to specify the minimum required data for each measurement load case and can be used to report the test database to demonstrate the minimum data requirements have been fulfilled. The number of bins in the matrices should be adapted for each specific measurement campaign based on the MEC operating states and control points.

6.4.6.2 Power production

During the measurement campaign, the data in the capture matrix should be classified according to the power matrix for WECs as in IEC TS 62600-100, the methods of bins for TECs as in IEC TS 62600-200 or the method of bins for river energy converters as in IEC TS 62600-300.

6.4.6.3 Parked

The parked measurement load case has the MEC in the parked state (either standstill or idling without power production; see Table 4). When more data sets are collected than the minimum listed in the capture matrix, only the minimum required need to be reported. If there are more than one parked state or more than one excitation state that can have a relevant influence on the structural loading, then a separate measurement should be performed for each parked state or excitation state.

Table 4 – Capture matrix for parked condition

Parked	
Time series record length	**In a stable condition**
Parking modes	Normal parked state
Water speed and/or wave energy flux	As high as possible
Minimum data requirement	1

6.4.6.4 Transient events

The capture matrices for the transient events are given in Table 5 and Table 6. The minimum number of repetitions and the power level are indicated. The emergency shutdown and grid failure should be performed at rated power.

Table 5 – Capture matrix for normal transient events

Normal start-up and shutdown events			
Event	**Power level:**	**Around 10 % of rated power**	**Rated power**
Start-up	Minimum required repetitions:	3	3
Normal shut-down	Minimum required repetitions:	3	3

Table 6 – Capture matrix for other than normal transient events

Other transient events		
Event	**Target conditions**	**Minimum required repetitions**
Emergency shutdown	Rated power	3
Grid failure	Rated power	3

6.5 Measurement load cases for MECs with blades connected to a rotor shaft

6.5.1 General

For MECs with blades connected to a rotor shaft the MLCs of 6.4 shall be used, except for those MLCs that are specified in 6.5.

Through the technology qualification process of 5.3, the MLCs can be adapted to the specific MEC.

6.5.2 MLCs for dynamic characterization

Table 7 provides the measurement load cases that are recommended for the dynamic characterization of the MEC frequencies. The table also provides the targeted frequencies for each MLC.

Table 7 – MLCs for dynamic characterization

MLC number	Measurement load case	DLCs IEC TS 62600-2:2019, Table 7 and Table 8	Target frequencies	Comment
3.1	Power production	1)	Blade, drivetrain and substructure frequencies[c]	Normal operation with relatively steady rotational speed
3.2	Parked[a]	6)	Blade and substructure frequencies[c]	MEC is parked (standstill or idling)
3.3	Emergency stop	5)	Blade, drivetrain and substructure frequencies[c]	Emergency stop from rated power
3.4	Artificial excitation[b]	Low water speed and wave energy flux	Blade frequencies	The artificial excitation can be performed under controlled conditions like in a sheltered harbour.

[a] High enough water speed and/or wave energy flux to get sufficient excitation, this will be MEC specific.

[b] Low enough water speed and wave energy flux to not have the excitation affected by other hydrodynamic loads. Testing may be done in a sheltered harbour, for example a decay test for a WEC and a pulling test for a CEC.

[c] Depending on the WEC or CEC configuration the target frequencies can also be foundation frequencies, floating device frequencies or mooring system frequencies.

6.5.3 Capture matrices

6.5.3.1 General

For MECs with blades connected to a rotor shaft the capture matrices of 6.4.6 shall be used, except for those specified in 6.5.3.

6.5.3.2 Parked

The parked measurement load case has the MEC in the parked state (either standstill or idling). For MECs where the rotor axis is controlled to be in line with or perpendicular to the current or wave direction (whichever is applicable), yaw misalignment can cause high loading on the blades. One time series should be collected with target values of 30° yaw misalignment, one with 0° yaw misalignment and one with –30° yaw misalignment (see Table 8 and Annex B).

When more data sets are collected than the minimum listed in the capture matrix, only the minimum required need to be reported.

Table 8 – Capture matrix for parked condition

Parked			
Time series record length	**10 min**		
Parking modes	Normal parked state (for example, idling, standstill)		
Target yaw misalignment	–30	0	30
Water speed or wave energy flux	As high as possible	As high as possible	As high as possible
Minimum data requirement	1	1	1

If there are other operating states or excitation states that can have a relevant influence on the structural loading these operating states or excitation states should be added.

6.6 Quantities to be measured for all WEC and CEC

6.6.1 General

The main objective of mechanical load measurements is the verification of the design load model of the tested MEC type. This is performed by repeating the analysis with the model parameters adjusted to match the measured site conditions. Therefore, it is essential to have a good representation of meteorological and oceanographic quantities as well as the operation quantities in order to compare measured and simulated load quantities.

The relevant physical quantities to be determined in order to characterize the loading of MECs can be classified into the following:

- load quantities (for example, prime mover loads and substructure loads);
- oceanographic quantities (for example, current velocity, current turbulence, wave energy flux and wave period);
- meteorological quantities (for example, wind speed and direction, air density);
- operation quantities (for example, power production, rotational speed, pitch angles, yaw misalignment, rotor azimuth angle, operational state).

Mandatory and recommended measurements as listed in Table 9, Table 10, Table 11, Table 12 and Table 13 are found to be important for model validation. There is a risk in not performing the recommended measurements as these may be helpful for explaining differences between the simulated and measured data.

The load quantities to be measured should be selected at the following structural areas:

- the structural interfaces between the subsystems or structural components;
- those parts of the structure where calculations show the smallest safety factors against buckling, strength or fatigue life;
- the structural areas of uncertainty (e.g. wave slamming loads);
- areas that can deliver information about the load distribution over a subsystem or component.

Through the technology qualification process of 5.3, the quantities to be measured can be adapted to the specific MEC.

6.6.2 Load quantities

The loads that shall be measured are listed in Table 9. These are the most important loads on crucial locations of the MEC structure. With these loads the simulation results can be validated and from these loads the loading of the relevant MEC structural components can be derived. See Figure 1 and Figure 2 for a scheme of the subsystems.

Table 9 – All WEC and CEC load quantities

Load quantities	Level of importance
Loads in the prime mover at or near a point where it connects to the PTO	Mandatory
Loads in the PTO at or near a point where it connects to the substructure and/or the foundation or to a floating device [a]	Mandatory
Station keeping loads in two perpendicular directions [a]	Mandatory
Prime mover absolute and relative position [b]	Mandatory
PTO absolute and relative position [b]	Mandatory
Floating device absolute and relative position [a,b]	Mandatory
Loads exerted on the prime mover. For example, in high stress structural components like in slender parts of the prime mover, or loads at or near connection areas between structural components of the prime mover	Recommended
Load at or near a point where a control action is exerted, for example a brake action or an end stop	Recommended

[a] If a floating device and mooring system is part of the MEC configuration. Station keeping loads can be measured in a single direction when the perpendicular loads are shown to be negligible.

[b] If applicable, also a velocity measurement and an acceleration measurement.

6.6.3 Meteorological and oceanographic quantities

Table 10 lists the oceanographic and meteorological quantities to be measured.

Table 10 – Oceanographic and meteorological quantities

Quantity	Level of importance
Current speed	Mandatory
Current direction	Mandatory
Water temperature	Mandatory
Current turbulence intensity (for tidal and other current energy converters)	Mandatory
Current vertical distribution (for tidal and other current energy converters)	Mandatory
Surface elevation and water depth[a]	Mandatory
Ice accretion potential[b]	Recommended
Wind speed[b]	Recommended
Wind direction[b]	Recommended
Air temperature[b]	Recommended
Air humidity[b]	Recommended
Atmospheric pressure	Recommended

[a] From the surface elevation measurements the directional wave spectrum should be derived.

[b] For MECs with structural components above the free surface.

6.6.4 MEC operation quantities

Table 11 lists the operation quantities to be measured.

Table 11 – MEC operation quantities

Quantity	Level of importance
PTO power input and output	Mandatory
Position of Prime Mover	Mandatory
Operational state control system	Mandatory
Control system input data and status	Mandatory
Brakes loading (if not possible, brake pressure) [a]	Recommended
Draft or freeboard of the floating device [b]	Recommended
End stop loading [c]	Recommended

[a] If a mechanical braking device is part of the braking system.

[b] If a floating device is part of the MEC configuration.

[c] If one or more end stops are part of the MEC configuration.

It is recommended to measure the kinematic component (e.g. linear or angular velocity, hydraulic flow rate or electrical current) and the dynamic component (e.g. force, torque, hydraulic pressure or electrical voltage) of the PTO input power as well as the PTO output power. Both components can have a direct influence on the loads in the structure (e.g. frequencies for the kinematic component and stresses for the dynamic component of power).

Control system operational state information (for example, normal operation, load control operation, idling, grid connection, emergency shutdown, protection system activation, etc.) is necessary in order to properly categorize recorded data. In those cases where several operational states (e.g. normal operation and load control) are used during the load measurement campaign it is recommended that automatic data acquisition of the different modes is implemented.

Control system input data and status signals indicate for example online/offline and faulted/not-faulted conditions.

6.7 Quantities to be measured for MECs with blades connected to a rotor shaft

6.7.1 General

In 6.7 the load quantities and MEC operation quantities for MEC configurations with blades connected to a rotor shaft are described. These are specifications of the general load quantities and MEC operation quantities in 6.6.

The PTO of a MEC with blades connected to a rotor shaft can be supported:

- by a substructure and/or foundation that is connected to the seabed or shore;
- by a floating device which is moored to the seabed or shore.

These requirements are valid for a MEC with blades connected to a rotor shaft of which the PTO is connected with a tubular column to a substructure/foundation or to a floating device. In case of special designs (e.g. structured supports, hybrid or two part connected blades, active hydrodynamic controls on the blades, etc.) additional measurements may be required for model validation.

Through the technology qualification process of 5.3, the MLCs can be adapted to the specific MEC.

6.7.2 Load quantities

The loads to be measured are listed in Table 12. These are the basic loads on crucial locations of MEC construction from which the loading in the relevant MEC structural components can be derived. The turbine loads are also given in Figure 5.

Table 12 – MECs with blades connected to a rotor shaft load quantities

Load quantities	Level of importance
Blade root flatwise bending moment (M_{bf})	1 blade mandatory additional blade recommended
Blade root edgewise bending moment (M_{be})	1 blade mandatory additional blade recommended
Rotor torque (M_r)	Mandatory
Base of tubular column normal moment (M_{cn})	Mandatory
Base of tubular column lateral moment (M_{cl})	Mandatory
PTO absolute and relative position	Mandatory
Rotor tilt moment (M_{tilt})	Recommended
Rotor yaw moment (M_{yaw})	Recommended

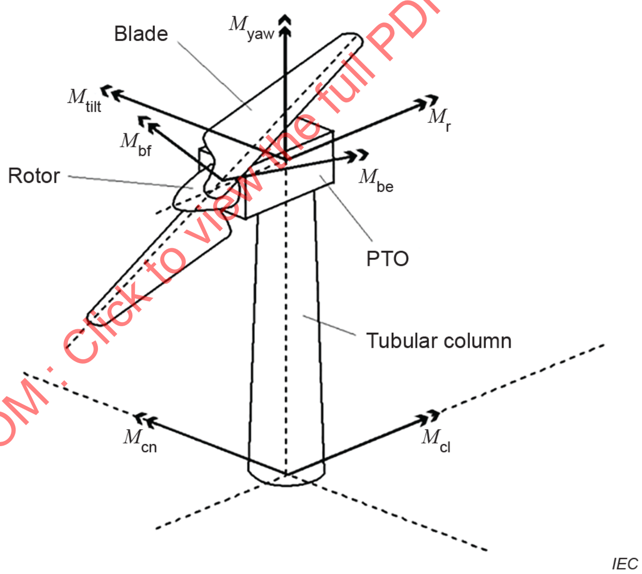

Figure 5 – Turbine loads: rotor, blade and base of tubular column loads

6.7.3 Oceanographic and meteorological quantities

See 6.6.3 for the oceanographic and meteorological quantities.

6.7.4 MEC operation quantities

Table 13 lists the operation quantities to be measured for MECs with blades connected to a rotor shaft.

Table 13 – MEC with blades connected to a rotor shaft operation quantities

Quantity	Level of importance
PTO power output	Mandatory
Rotor speed or generator speed [a]	Mandatory
Yaw misalignment	Mandatory
Rotor azimuth angle	Mandatory
Pitch position of all instrumented blades turbine controller output [b]	Mandatory for all instrumented blades Recommended for all blades
Pitch speed [b]	Mandatory
Operational state control system	Mandatory
Control system input data and status	Mandatory
Brake status [c]	Mandatory
Brake moment (if not possible, brake pressure) [c]	Recommended
NOTE Pitch speed can be derived from pitch position	

[a] If an electrical generator with a speed proportional to the rotor speed, is part of the PTO.

[b] If mechanical blade pitching is part of the prime mover.

[c] If a mechanical braking device is part of the primary braking system.

6.8 MEC configuration changes

No changes that impact the test results should be made to the test MEC during the test. Any change that has been made to the MEC shall be reported by the manufacturer and shall be included in the test report.

The manufacturer shall classify the changes into the following categories:

a) Changes without any significant impact on loads: Data from before and after the change can be used within the same database.

b) Changes with significant impact on loads:

   1) Temporary changes: this data shall be excluded from the database;

   2) Persistent changes, even though they can be cross simulated with the same simulation model after implementation of the same change in the model, these periods shall be segregated into a separate database;

   3) Changes that resolve a problem and bring the MEC into the state it should have been in before, therefore this shall result in a re-start of the campaign.

The capture matrix requirements (see 6.4.6 and/or 6.5.3) should be fulfilled with at least one configuration where no changes are made with significant impact on loads.

7 Instrumentation

7.1 Load quantities for all WEC and CEC

7.1.1 General

Through the technology qualification process of 5.3, the load quantities can be adapted to the specific MEC.

7.1.2 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).

For MECs, it will seldom be possible to place a load cell in a main load path, except for mooring and tether loads. For this reason, strain gauges applied to the structure are selected as the recommended type of sensor and thus 7.1 focuses on the use of electrical and optical strain gauges. If alternative load sensors are used the requirements should be adjusted accordingly. Load sensors are calibrated by applying quasi-static loads. It is important to realize that dynamic behaviour of the structure or structural 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 MEC applications. To allow for evaluation and correction of the temperature effects it is recommended to measure the surface temperature near strain gauge locations. Dummy strain gauges can be used also to correct for the temperature effect in postprocessing. These are strain gauges that are not coupled to the strained surface but are mounted in the same temperature field (see also Annex D).

Water ingress to the sensors is likely to adversely affect the strain measurement. It is recommended to install strain gauges inside the material or inside the structure during manufacture if possible. Sensor redundancy is recommended. Fibre optic strain gauges have been used in some applications as they are less sensitive to environmental effects. For submerged offshore devices temperature effects might be a relatively minor problem.

During the loading of structural components, internal parts of the components, such as the shear webs of rotor blades, might deform plastically and this might change the relation between the measured strain and the calculated loading. It is therefore recommended to perform the calibration of this relation (before and after the loading) in these cases where a plastic deformation can be expected, and it is recommended to report the measured strain also. In the case of bending loads, it is recommended to measure the strain at the tension side as well as at the compression side.

7.1.3 Choice of sensor location

In the process of selecting sensor positions for the measurement of 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;
- is in a region of uniform stress (i.e. is not subject to high stress/strain gradients, avoids localized stress concentrations);
- has space to apply sensors;
- allows temperature compensation;
- is made of isotropic material (for example, steel is preferable to composite materials);
- is made of material to which measurement devices can be easily fixed or bonded.

7.1.4 The connection between prime mover and PTO

In the connection between PTO and prime mover there is commonly a rotational shaft or a translational shaft combined with other mechanical connections like hinges or bearings. For

MECs with a rotational or a translational shaft the mechanical loads measurement can best be performed on the shaft itself. If this is not possible then the mechanical loads can be measured at the other mechanical connections like at or near a hinge or bearing.

7.1.5 The connection between PTO and substructure and/or foundation

7.1.5.1 General

The PTO is most commonly either directly fixed to the substructure and/or foundation or through a mechanical mechanism for example a yaw mechanism. The mechanical loads can be measured at or near the fixed connection to the substructure and/or foundation or at or near the connection of the mechanical mechanism. In some cases, the loads on the mechanism can be derived from parameters of the mechanism, such as the oil pressure inside a hydraulic cylinder. Friction effects should be taken into account.

7.1.5.2 Substructure mechanical loads

The substructure commonly consists of tubular components like columns. These columns can be parts of lattice structures. The loads can be measured at the columns, preferably at locations that comply with the recommendations of 7.1.3. For substructures with entirely different shapes, the recommendations of 7.1.3 can also be applied.

7.1.5.3 Measurement of foundation loads

It can be very difficult to measure foundation loads directly. In general, the foundation material is not suited (e.g. concrete), or the position is difficult to reach (e.g. deep under the free surface). In those cases, the foundation loads can best be derived from loads measured at the substructure or PTO.

7.1.6 The connection between PTO and floating device

For a moveable connection between the PTO and a floating device 7.1.4 can be applied. In general, the dynamics of a floating device are more complex than the dynamics of a fixed device due to the added degrees of freedom and the dynamics of the floating device and the mooring system. Care should be taken that these dynamic effects are taken into account.

7.1.7 Measurement of station keeping loads

7.1.7.1 General

In most floating MEC configurations, there are catenary or tensioned mooring lines connecting the floating device to the seabed or shoreline (see also IEC TS 62600-10). In those cases, it is mostly possible to place a loadcell between the mooring line and the floating device. Care should be taken that a failure (i.e. rupture) of the loadcell does not lead to a failure of the mooring system.

7.1.7.2 Measurement of tether loads

Tether loads can be measured in the same way as mooring line loads. However, in some tether configurations it is not possible to place a loadcell between the tether and the floating device or between the tether and the prime mover. In those cases, it might be possible to place strain gauges on a part of the tether itself. The recommendations of 7.1.3 should be taken into account.

7.1.8 Prime mover absolute and relative position

Prime mover position should be measured in all relevant degrees of freedom. The relative position of the prime mover to the PTO, can be measured directly by an encoder or provided by the MEC controller. If the controller signal is used, the latency should be evaluated and addressed. The prime mover velocity can be derived from the prime mover position measurement.

Prime mover acceleration can lead to high inertia loads being exerted on the PTO. Special attention should be paid to the resonance frequencies of the prime mover. Accelerometers should be used to measure PTO acceleration. Care should be taken when selecting the accelerometers to account for their low-frequency phase shift and amplitude characteristics.

7.1.9 PTO absolute and relative position

The PTO position should be measured in all relevant degrees of freedom. The PTO velocity can be derived from the prime mover position measurement.

The PTO acceleration will give information about the structural rigidity and the loading between the PTO and other subsystems. The PTO frequencies will give information about the natural frequencies and related excitations. Accelerometers should be used to measure PTO acceleration.

When the PTO can make a controlled movement relative to the substructure or floating device, the relative position of the PTO to the substructure or floating device, can be measured directly by an encoder or provided by the WEC or CEC controller. If the controller signal is used, the latency should be evaluated and addressed.

7.1.10 Substructure or floating device absolute and relative position

It is recommended to measure the position of the substructure or floating device in compliance with IEC TS 62600-100, IEC TS 62600-200 or IEC TS 62600-300. Alternatively, the position of the PTO can be measured in a similar manner.

The floating device acceleration will give information about the loading of the floating device (e.g. wave loading) and the inertia loading exerted on the PTO and prime mover. This information can be derived from the spectral density of the acceleration. Accelerations should be measured with accelerometers.

7.1.11 Water pressure measurements

In some MEC configurations water pressure measurements can be used as a form of direct load measurement on surfaces, especially with wave loading. With the pressure measurement the relation between the hydrodynamic loading and the strain measurement can be established. Water pressure can be measured by installing pressure sensors on surfaces. Pressure sensors should be mounted so that the sensing element is flush with the surface. Sensors should be positioned in flat or curved surfaces away from obstructions. A stiff connection is required so that the sensor is held firmly in position. Flexible areas of the structure should be avoided. In general, there are two types of sensors used. Hydrostatic pressure sensors are used to measure fatigue pressures and impulse pressure sensors are used to measure slam and impact pressures. The measurement of impulse pressures requires high sample rates and the capture of short duration timeseries may be triggered by the pressure exceeding a threshold value. The number of sensors used will depend on the criticality of the pressure distribution over the subsystems of the MEC.

7.2 Operation quantities for all WEC and CEC

7.2.1 General

Through the technology qualification process of 5.3, the operation quantities can be adapted to the specific MEC.

7.2.2 Electrical power

The MEC's electrical power output can be measured at any point as long as it is properly described. Measuring it in compliance with the IEC TS 62600-100, IEC TS 62600-200 or IEC TS 62600-300 is recommended. Output from the MEC controller is acceptable.

7.2.3 Hydraulic power

For MECs with a PTO with a hydraulic intermediate stage between mechanical power and electrical power, it is recommended to measure the hydraulic power (pressure and flow rate). From the hydraulic power the loads exerted on the PTO can be analysed. Especially, hydraulic pressure peaks and/or pressure frequencies can be helpful in analysing the PTO loading. Care should be taken that friction losses are taken into account.

7.2.4 Generator speed

Generator speed can be measured on the generator shaft. Consideration should be given to assure that the sample rate is high enough to acquire an accurate speed measurement. For synchronous generators, generator speed can also be derived from the electrical frequency. Output from the MEC controller is acceptable.

7.2.5 Brake moment or force

The method of measuring the brake moment or force depends on the MEC configuration. In some MEC configurations the brake pressure (hydraulic or spring pressure) can be measured and when the relationship between brake pressure and brake moment or force is known, the brake moment or force can be derived. In other MEC configurations the brake moment can be measured by measuring the torque on the reaction arm, or by measuring shaft torque or force on both sides of the brake, or through analysis of deceleration time with a known inertia.

7.2.6 MEC status

MEC status can be measured using controller signals (e.g. grid connection, emergency shutdown, protection system activation).

7.2.7 Brake status

Brake status should be measured, either directly (e.g., proximity sensor) or indirectly (brake pressure or MEC controller; in which case latency needs to be evaluated).

7.2.8 Draft or freeboard measurement

With the recommended measurements of the floating device draft or freeboard, mechanical malfunction can be signalled at an early stage. The draft measurement could give information about a displacement of the centre of gravity, which could for example mean leakage of water inside the floating device or a shift in mechanical loads or weights.

7.3 Load quantities for MECs with blades connected to a rotor shaft

7.3.1 General

7.3 gives extra specifications for the load quantities of the MEC configurations with blades connected to a rotor shaft.

Through the technology qualification process of 5.3, the load quantities can be adapted to the specific MEC.

7.3.2 Blade root bending moments

Flatwise and edgewise bending moments should be measured. For handling and environmental protection, it is recommended that the sensors be mounted within the blades rather than on the outer surface, where convenient.

Strain gauge bridges should ideally be applied perpendicularly to a nearly cylindrical blade root, so that cross-sensitivities are minimized. Regardless of the mounting location, cross-sensitivity should be measured, and should be addressed (i.e. through correction or increased uncertainty). For ease of analysis, the set of gauges should be oriented in line with the blade coordinate system.

7.3.3 Blade bending moment distribution

Blade bending moment distribution can be measured using additional sets of strain gauges located at a cross section at least 30 % or as far as practically possible up to 50 % of rotor radius. Other requirements from 7.1.3 and 7.3.2 also apply. For the bending moment distribution the coordinate system should be clearly defined.

7.3.4 Blade torsion frequency/damping

The blade's first torsional frequency and damping can be estimated using strain measured with a half or full torsion strain-gauge bridge through operational modal analysis. Since neither the frequency nor the damping rely on absolute magnitude of the measurement, no calibration of this signal is required.

7.3.5 Rotor yaw and tilt moment

Asymmetrical rotor loads should be measured on the primary load path as close to the rotor shaft as possible. The preferred method for the measurement of rotor yaw and tilt moments is through two perpendicular bending bridges on the main shaft along with the hub azimuth position measurement. It is recommended that the main shaft strain gauges be positioned in line with the instrumented rotor blade.

On some MECs, it may not be possible to apply strain gauges to the shaft. In such cases, it is recommended to install gauges for bending moments in the non-rotating system, either on the shaft-support or in the top of the tubular column.

7.3.6 Rotor torque

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 on only one location on the shaft surface, shear due to bending and transverse load will be interpreted as torque. If torque measurements on the shaft are not possible, PTO bending gauges and yaw position are permitted. Power and rotor speed should not be used as a substitute to measure rotor torque.

7.3.7 Tubular column bending

7.3.7.1 General

The tubular column bending is preferably measured at the base where the tubular column connects to the substructure and/or foundation or to a floating device. At the base the bending moments have the highest values. When this is not possible the bending moments can be measured at the top where the tubular column connects to the PTO, or at any other location along the tubular column.

The bending moments at the tubular column base should be measured in two perpendicular directions. These bending moments should be measured using full strain gauge bridges mounted as close to the base flange as possible while avoiding disturbances from load introduction effects for the base flange, etc. As a rule of thumb, base bending gauges should be placed at least one tubular column diameter from any flange.

7.3.7.2 Lattice support structure bending

A lattice support structure, instead of a single tubular column, connecting the PTO with a foundation or a floating device, will require strain measurements in all supporting legs to arrive at the resultant base bending load for all current and wave directions. A special assessment of the strain pattern in the lattice support structure and the consequence for the measurements should be performed.

7.3.8 Darrieus style rotor bending

Darrieus (or cross-flow) style rotors have structures that connect the blades to the rotor shaft. The MLCs and instrumentation should be the same as with the MECs with blades connected to a rotor shaft with the addition of the measurement of the relevant bending moments in the connecting structures, plus the radial force in the connecting structures. In the case that the connecting structures and the simulated loading are the same for every connecting structure, the measurements can be performed on a single blade connecting structure.

7.3.9 PTO and blade absolute and relative position

If applicable, the accelerometers should be mounted on that part of the PTO that yaws with the rotor.

If applicable, blade pitch angle should be measured directly by an encoder or provided by the MEC controller. If the controller signal is used, the latency should be evaluated and addressed.

7.4 Operation quantities for MECs with blades connected to a rotor shaft

7.4.1 General

7.4 gives specifications of the operation quantities for the MEC configurations with blades connected to a rotor shaft.

Through the technology qualification process of 5.3, the operation quantities can be adapted to the specific MEC.

7.4.2 Rotor speed or generator speed

Rotor speed can be measured on either the low-speed shaft or high-speed shaft (in case of a gear box). If rotor speed is measured on the low-speed shaft, additional consideration should be given to ensure a sufficiently high resolution of rotor speed is acquired. If rotor speed is measured on the high-speed shaft, additional consideration should be given to assure the sample rate is high enough to acquire sufficient resolution. Output from the MEC controller is acceptable.

7.4.3 Yaw misalignment

Yaw misalignment should be derived from wave/current direction and yaw position. Yaw position can come from the controller only if calibration verifications are performed regularly. Caution should be used on the 360° – 0° transition and the location of the dead band, if present. Other measurement techniques may be used, when it is documented that the accuracy and uncertainty of the measurement technique is equivalent or better to the measurement determined from current/wave direction and yaw position.

7.4.4 Rotor azimuth angle

Rotor azimuth angle should be measured on the low-speed shaft, high-speed shaft (with reset on the low speed shaft) or provided by the MEC controller. If the controller signal is used, the latency should be evaluated and addressed. Caution should be used on the 360° – 0° transition.

7.4.5 Pitch position

For MEC configurations with pitchable blades, the blade pitch angle should be measured directly by an encoder or provided by the MEC controller. If the controller signal is used, the latency should be evaluated and addressed.

7.4.6 Pitch speed

For MEC configurations with pitchable blades, the pitch speed should be measured either directly or derived from pitch position during post-processing of the data.

7.4.7 Brake moment

How the brake moment is best measured depends on the turbine configuration. Examples are; verifying brake pressure (hydraulic or spring pressure) with assumed coefficient of friction, measuring on the torque reaction arm, by measuring shaft torque on both sides of the brake or through analysis of deceleration time.

7.5 Oceanographic and meteorological quantities

7.5.1 General

Through the technology qualification process of 5.3, the oceanographic and meteorological quantities can be adapted to the specific MEC.

7.5.2 Measurement and installation requirements

The requirements given in IEC TS 62600-100, IEC TS 62600-200 or IEC TS 62600-300 should be followed for the installation and measurement of meteorological and oceanographic quantities. If no guidance is given in these standards the instructions of the manufacturer should be followed.

7.5.3 Sea or river ice loads and ice accretion

Load tests of MECs that should be able to resist sea or river ice loading and/or ice accretion, are not specified in this document.

Sea or river ice and ice accretion should be considered according to Annex C. In addition, sea ice loads should be considered in combination with motions of the prime mover, PTO and substructure or floating device, due to loads from ice, wind, wave or current processes. The flexibility of the mooring system should be considered when determining sea ice loads.

If sections of the mooring system and electrical cable are exposed to sea ice loads, such loading should be considered.

An ice-management system may be used to reduce loading due to ice action. The effect of ice-management on the behaviour of the MEC should be taken into account in the design.

7.6 Data acquisition system (DAS)

7.6.1 General

A DAS is used to acquire analogue or digital signals from one or more sources and convert these signals into digital form for analysis or transmission by end devices such as digital computers, recorders, or communications networks. The ability of the DAS to preserve signal accuracy and integrity is the main measure of the quality of the system.

7.6.2 Resolution and sampling frequency

For analogue signals the resolution of the A/D converter is the fundamental measure of system accuracy of the DAS. The number of bits in the A/D converter determines the resolution of the system. The sampling rate and resolution are sufficient when the highest frequencies that can be expected, are captured accurately. High frequencies can occur for example because of wave slamming loads and snatch loads on moorings.

7.6.3 Anti-aliasing

The DAS should have aliasing protection on all load channels. The aliasing protection has two equally important purposes: the first is to prevent the creation of aliased frequency components in the specified frequency range and the second is to sample input waveforms with sufficient fidelity to support the test objective.

For each analogue channel in the measurement campaign, the following items should be reported:

- A/D resolution;
- sampling frequency, f_s;
- anti-aliasing filter type or anti-aliasing strategy (if done digitally);
- cut off frequency setting for the filter, f_c.

8 Determination of calibration factors

8.1 Overview

Through the technology qualification process of 5.3, the determination of calibration factors can be adapted to the specific MEC.

8.2 General

Clause 8 provides the calibration methods for the instrumentation in Clause 7. In general:

- Linear calibrations are assumed. For the majority of situations this is valid. Any non-linear behaviour can be dealt with through application of non-linear calibration coefficients or by adding uncertainty in the measurements.
- All elements of the measurement chain should be calibrated.
- Calibrations should be performed with the same instrumentation used to record the test data.

For several sensors, different methods are used for determination of the offset and the sensitivity.

The calibration process is the characterization of the measurement chain (sensor, cabling, electronics, etc.) to a known external standard. The choice of calibration method is largely determined by the choice of external standard and should take into account the following factors. The calibration method should:

- cover as much of the measurement range as possible;
- minimise disturbances;
- be repeatable;
- be sufficient to determine both the slope, offset and, if necessary, the cross-talk of the signal.

The best way to ensure measurement accuracy is to measure the full channel response directly 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. 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.

Several methods exist for calibration of the load sensors and it is recommended to use more than one calibration method in order to verify the calibration results. Suitable calibration methods are:

- analytical calibration;
- gravity or buoyancy loads;
- application of external loads.

The preferred method used for calibration is the one that leads to the lowest overall uncertainty and is a factor of:

- accuracy of used information;
- the load range covered by the calibration.

Additionally, the feasibility and cost of the methods will impact which calibration method would be used.

All offshore calibrations should be conducted at low wave energy flux and/or current speed in order to minimize hydrodynamic loading of the MEC and at low and steady rotational or translational speed in order to minimize inertia effects and hydrodynamic forces.

In case gravity or buoyancy loads are used for calibration of a load sensor, the information used to derive the applied loads should be provided by the manufacturer. Gravity or buoyancy loads can only be applied when the load is at least 50 % of the calculated maximum loading of the structural component. The gravity or buoyancy loads can generally only be applied for the calibration of the offset.

The remainder of this clause provides the requirements for calibrations that are unique for mechanical loads testing.

8.3 Calibration of load channels for all WEC and CEC

The calibration of the load channels can best take place in a laboratory environment, where external but known loads can be applied to the various parts of the MEC. The parts can be loaded for example with winches or hydraulic or electrical actuators connected to load cells. If the influence of the (sea) water is necessary for the calibration, this process can take place in a basin or in a sheltered harbour.

8.4 Calibration of non-load channels for all WEC and CEC

The calibration of non-load channels can also best take place in a laboratory environment, where control settings can be applied to the MEC and the resulting measurement of the non-load channels can be calibrated. If the influence of (sea) water is necessary for the calibration, this process can take place in a basin or in a sheltered harbour.

For calibration of the oceanographic and meteorological measurement devices refer to IEC TS 62600-100, IEC TS 62600-200 or IEC TS 62600-300 as applicable.

8.5 Calibration of load channels for MECs with blades connected to a rotor shaft

8.5.1 General

8.5 provides specifications for calibration methods for the load channels for MEC configurations with blades connected to a rotor shaft. See the overview in Table 14.

Table 14 – Summary of suitable calibration methods

Measured quantity	Analytical	External load	Gravity or buoyancy
Blade bending moments		S,O	O
Main shaft torque[a]	S	S,O	
Main shaft bending	S	S,O	O
Tubular column bending moments[a]	S	S,O	O
S : suitable for slope O : suitable for offset			
[a] For suitable methods for determining the offset, see 8.5.3 and 8.5.4.			

With external loading the offset can generally be determined by applying the load from different directions and/or by rotating the structural component under different angles. For example, by rotating the structural component at three angles of 120° over a full rotation of 360° under gravitational loading. Because of the relatively high loads on a MEC, the offset will generally be small compared to the full measurement range.

8.5.2 Blade bending moments

8.5.2.1 Analytical calibration

In general, the analytical calibration is not feasible for calibration of the blade bending moments as the material properties are not well known.

8.5.2.2 Gravity or buoyancy loads

Gravity or buoyancy calibration of the blade bending sensors requires knowledge of the blade mass moment at the instrumented cross section. It is achieved by exposing the sensor to a well-defined moment caused by gravity or buoyancy. This can be done by either idling the rotor at different pitch angles, or by fixing the blade in a horizontal position and pitching the blade to different pitch angles. In general gravity or buoyancy loads will only be suitable for calibrating the offset.

8.5.2.3 External loads

During a calibration of the blade bending moment sensors with an external load, a known load is applied at a known location along the blade and in a known direction. The yoke that exerts the external load on the blade should not damage the blade. Therefore, this information is required:

- maximum permissible edgewise load at the blade yoke position;
- maximum permissible flatwise load at the blade yoke position;
- rotor cone angle.

The following hardware is required:

- blade yoke;
- cable;
- pulling device;
- calibrated load cell;
- calibrated strain gauge measuring system.

Calibration procedure:

- fasten the blade tip yoke to the blade;

- fasten the cable to the yoke;
- fix the rotor in a stable position;
- pull the cable in two perpendicular directions for the flatwise and edgewise bending;
- record the applied force and the measured strains with the same measuring system;
- find the sensitivity from the correlation of the applied load and the strain gauge output.

Other methods can be used if these can lead to the same accuracy of results.

8.5.3 Main shaft moments

8.5.3.1 Analytical calibration

Analytical calibration is done by scaling the sensor output to material strain by gauge factor, bridge configuration and measurement chain, and then scaling the measured strains to moments using cross-section geometry and material properties. An analytical calibration can be performed on shafts with near constant cross-sectional properties and well-known material characteristics and thus only for areas with minor stress concentration factors.

8.5.3.2 Gravity or buoyancy loads (bending only)

The offset of the signal can be determined from the azimuth averaged signals during the slow rotor rotation. The expected moment range at the measurement location during a slow rotor rotation should be provided by the turbine manufacturer.

8.5.3.3 External load

During a calibration through application of an external load, the scaling factors are determined by applying a known moment on the main shaft (e.g. by pulling on a blade using a calibrated load cell see 8.5.2.3) and recording the sensor's response to the applied moments.

If the external load can only be applied in one direction and the structure is geometrically symmetric, the obtained scaling factors can also be used for other directions (e.g. using the tilt moment on a non-rotating shaft to calibrate the yaw moment on that same shaft).

8.5.3.4 Calibration of torque through power and rotor speed

Besides the earlier mentioned methods of applying an external load or performing an analytical calibration, the rotor torque could also be calibrated by measuring power output and rotor speed, taking the drive train efficiency and the turbine's power consumption into account.

The offset of the shaft torque signal can be determined by slow rotations at low wave energy flux and/or current velocities below start-up of power production.

8.5.4 Tubular column bending moments

8.5.4.1 Gravity or buoyancy loads

Typically, the PTO and rotor have a centre of gravity that is not directly above the neutral axis of the tubular column. For MECs with an actively controlled yawing mechanism, this distance causes an overhang moment which can be used for the calibration of the offset of the tubular column bending sensors. The average value of the sensor output during the yaw rotation is the offset value. Gravity or buoyancy calibration of the tubular column bending sensors requires knowledge of the MECs head (PTO and rotor) mass moment with regard to the tubular column axis[1]. 360° yaw rotations of the PTO will expose each sensor to the negative and positive gravity or buoyancy moment during one revolution.

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1 Note that the gravity or buoyancy moment may be dependent on the blade pitch angle if applicable.

8.5.4.2 Analytical

Analytical calibration is done by scaling the sensor output to material strain by gauge factor and strain gauge bridge configuration and then scaling the measured strains to moments using cross section geometry and material properties.

8.5.4.3 External loads

The tubular column can be loaded by a known external load at a defined location and direction to calibrate the slope. The offset can be derived from external loading in three or more directions divided evenly over 360°.

8.6 Calibration of non-load channels for MECs with blades connected to a rotor shaft

8.6.1 Pitch angle

For MECs with pitchable blades, calibration of pitch angle is performed relative to a reference mark at the blade root (normally 0°), which can also be used as a reference for placing the blade bending sensors. All instrumented blades should be pitched to at least 2 well defined positions at which the signal output and true angle can be correlated. The two positions should at least be 80° apart from each other. Calibration of the reference mark to a physical origin should be performed as well. Alternatively, this should be traceable through documentation. If the pitch angle is measured through the turbine controller, checks should be performed regularly to verify the slope and offset.

8.6.2 Rotor azimuth angle

The slope of the signal is typically derived by performing a few slow shaft rotations and scaling the signal range of the saw tooth shaped signal or number of pulses to match the 360° range or counting the number of pulses in a rotor revolution.

For the derivation of the offset a few methods are available using:

- a level on a defined surface on the shaft or hub;
- an inclinometer on a defined surface on the shaft or hub;
- rotor azimuth positions defined by applying the rotor lock if applicable;
- the blade bending moment signals and looking for the location of the maxima and minima during a slow rotor rotation.

8.6.3 Yaw angle

The yaw angle can be calibrated to a reference mark on the substructure or floating device. The position of the substructure and/or floating device can be calibrated by using a positioning system with an accuracy equal or better than a differential GPS. The differential GPS can be supported by compass, accelerometer or gyroscope measurements. The same reference and method and the same coordinate system should be used for the calibration of wave and/or current direction and substructure and/or floating device.

8.6.4 Oceanographic and meteorological

The same external reference and method and the same coordinate system should be used for the calibration of wave and current direction and yaw angle.

8.6.5 Brake moment or force

The calibration method for the brake moment or force depends on the method used to measure it. If the load is measured through:

- strain gauges, an analytical calibration should be used for the derivation of the sensitivity. For derivation of the offset value measurements should be used when the brake is not applied;
- pressure, calibrated instruments should be used in combination with an assumed coefficient of friction.

9 Data verification

9.1 Overview

Through the technology qualification process of 5.3, the data verification can be adapted to the specific MEC.

9.2 General

Data verification serves two purposes:

- to assure that the signals are being measured correctly (e.g. correct calibration factor applied etc.). The results of this verification should be reported in the test report.
- to verify that the acquired data remains valid and problems are identified quickly. For these checks, only the verification checks that were used (not their results) and their frequency should be reported in the test report.

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

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

The first stage verification of measured time series should be performed during commissioning of the measuring programme and is based on recordings at the specified or higher sampling rates. It is recommended to perform cross checks against simulation results at this stage.

If valid data were recorded under abnormal conditions (MEC or environmental, such as during extreme storms), they should be segregated into a special category for possible further analysis and not be part of the capture matrix for normal operation.

Any data filter or rejection criteria should be clearly documented in the load measurement report.

During the measurement period, data should be periodically checked in order to ensure high quality and repeatability of the test results.

9.3 Verification checks for all WEC and CEC

This subclause provides requirements and recommendation of verification checks that can be used to fulfil the data verification requirements.

The following checks are applicable to all measured quantities:

- Measurement values outside operational limits of sensors, data transmission and acquisition system should be excluded.
- Special attention should be paid in cases of extreme weather or operating conditions.
- Valid data should be based on suitable calibrations as described in Clause 8. The first part of the data verification is a formal check that calibrations have been carried out correctly.

- Sensor drift may be identified from measured data statistics. If the offset of a sensor is drifting, the normal operation data can become scattered or show two or more trend lines when plotting e.g. the 10-min mean values as a function of current speed or wave energy flux.
- Zero drift due to temperature should be checked, documented and accounted for. If any data correction is applied, it should be reported and taken into account during uncertainty estimations. Drift is best identified by monitoring signal levels in low current speed or wave energy flux 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.
- The frequency contents of signals should be checked to assure the proper frequencies show up (e.g. natural frequencies, frequencies related to rotational speed) and to get an indication of the signal to noise ratio and if applicable the noise source. The signal to noise relation is sufficient when the analogue signal conditioning appropriately removes the noise outside the relevant frequencies.
- 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 presence of noise.
- Data should be verified for presence of spikes. 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 or unrecoverable adjacent spikes should be rejected. If spikes are removed from the data series, the procedure should be recorded. Data sets where spikes have been detected should not be used for the summary statistics of that channel, unless the spikes have been corrected.
- Data should be inspected for presence of flat spots/dropouts. Rejection criteria will vary for each signal.
- Unrealistic differences between comparable quantities: in these cases, a comparison of the recordings of the two independent sensor sets should be made. If unexplainable differences are observed, the instrumentation should be re-checked and the suspect data should be excluded.
- Data time series may be accepted as valid even though some channels are not valid, provided such other channels are not listed as mandatory quantities in Table 9, Table 10, Table 11, Table 12 and Table 13, whichever is applicable. These data sets can thus be used to fulfil the capture matrix requirements.

9.4 Verification checks for MECs with blades connected to a rotor shaft

9.4.1 General

9.4 provides specifications of verification checks for MECs with blades connected to a rotor shaft.

9.4.2 Blade moments

Below are examples of verification checks for blade moments:

- The bending moments should correspond to the gravity or buoyancy moments when the MEC is idling at low current speed or wave energy flux.
- If the bending moment of more than one blade is measured, the bending moments of the different blades at the same radius from the hub centre should have the same 10-min mean and standard deviation.
- Below rated speed, the sum of the 10-min mean values of the in-plane bending moments at the blade roots times a factor dependent on the rotor diameter and strain gauge location should be close to the main shaft torque:

$$M_s \approx \frac{r}{r-1{,}5 \cdot r_g} \cdot \frac{B}{L} \sum_{i=1}^{L} M_{\mathrm{bi},i} \quad (1)$$

where

M_s is the 10-min mean main shaft torque (Nm);

$M_{\mathrm{bi},i}$ is the 10-min mean in-plane blade root bending moment of blade i (Nm);

B is the number of blades on the MEC turbine;

L is the number of blades instrumented for blade root bending moments;

r is the rotor radius (m);

r_{g} is the radius of strain gauge location (m).

This formula assumes the centre of hydrodynamic force to act at 2/3R.

- During a slow rotor rotation, the phase of the blade signal should correspond with the sequence of the blades.
- During a pitch rotation the phasing of the blade signals should match the circumferential position of the gauges used for the measurements.

9.4.3 Main rotor shaft

Below are examples of verification checks for main rotor shaft signals:

- The power output could be checked against the main rotor shaft torque signal at rated power. Using the following formula:

$$P = M_{\mathrm{s}} \cdot \Omega \cdot \eta \quad (2)$$

where

P is the power (W);

M_{s} is the main shaft torque (Nm);

Ω is the rotor speed (rad/s);

η is the efficiency of the components between point of main shaft torque measurement and point of power measurement.

- The two bending moments in the main rotor shaft, 90° azimuth phase apart, should have the same mean and amplitude when the MEC is idling at low current speed and wave energy flux. The mean values of the two bending moments in the main shaft should be close to zero when the MEC is idling at low current speed and wave energy flux. The phase difference between the signals in the rotating frame should correspond to the angle between the two strain gauge bridges.

9.4.4 Tubular column

Below are examples of verification checks for measuring signals at the tubular column:

- If applicable, a yaw rotation at low current speed and wave energy flux should be performed at intervals. The two bending moments in the tubular column at the same level, should show data with an approximate sinusoidal shape (offset by some angle) that should have the same mean and amplitude when the MEC is yawing through 360° at low current speed and wave energy flux. The amplitude should represent the rotor overhang moment of the machine. The mean values of the two bending moments in the tubular column should be close to zero when the MEC is yawing through 360°. The yaw position at which the maximum and minimum of each bending signal occurs should correspond to the circumferential location of the strain gauges.

A time series containing a yaw rotation can be used to verify the correctness of the coordinate transformation of the tubular column bending moments. All bending moments in the PTO coordinate frame should be relatively constant, one transformed signal should be close to zero and the other should be equal to the rotor overhang moment of the machine.

- The bending moment versus current speed and/or wave energy flux may be checked for realistic values.

10 Processing of measured data

10.1 Overview

Through the technology qualification process of 5.3, the processing of measured data can be adapted to the specific MEC.

10.2 General

Clause 10 provides the post processing requirements used to derive the results that shall be reported. Specifically, the following are discussed: time series analysis, summary load statistics, load spectra based on rainflow counted ranges and estimation of equivalent loads.

One of the first steps in data processing may be to calculate the required measurement quantities from the measured signals (e.g. water density from water temperature). The post processing that is described below will be performed on the required measured quantities and not necessarily the measured signals.

10.3 Load quantities

The basic product of a measurement loads campaign is the calibrated and validated time series data. However, these time series should be post-processed to provide summary statistics, damage equivalent loads and cumulative rainflow spectra to provide an index to the actual data sets.

For the load quantities (Table 9 or Table 12), the following should be computed for all normal 10- min operation data sets. Other intervals than 10 min can be used:

- the 10-min file statistics (minimum, maximum, mean and standard deviation);
- the binned 10-min statistics for each bin of the capture matrix;
- the 10-min damage equivalent load for a single fatigue exponent;
- the cumulative rainflow spectrum for all normal operation data sets;
- the identification of MEC natural frequencies using PSD of example data sets during operation/idling/transient event.

10.4 Current speed and/or sea state trend detection

Slow variation in current speed and/or sea state, for example steady increase in current speed during a 10-min data set, is not part of common simulated current field models and results in non-representative high turbulence intensity. In this case the correlation between loads and turbulence intensity may be misleading. Trended data sets should not be rejected, nor should the current speed or sea state be detrended. Parameters indicating the degree of trending should be reported.

Methods for detecting trended data should be based on a form of high pass filtering to detect the influence on the turbulence intensity caused by low frequency changes. Any detection method used should be described in detail in the report.

Similar effects may also appear for other oceanographic or meteorological quantities. Further data which are not reproducible in simulation such as yaw activity etc. should be taken into account. The manufacturer should include all of these effects for proper correlation between measurement and simulation data in the course of model validation.

10.5 Statistics

For each 10-min file the 10-min statistics (mean, maximum, minimum and standard deviation) should be calculated for all signals. Other time intervals are possible.

For signals that are angular measurements that pass through the 360° – 0° transition, (e.g. PTO yaw position, hub azimuth position, current direction), the direction of the unit vector average should be used to compute the mean of the signal and special care should be taken to ensure that there are no data points sampled during a 360° – 0 ° transition.

10.6 Rainflow counting

To determine damage equivalent loads (DEL) and the cumulative rainflow spectra, the load quantity time series should be rainflow counted. Only the ranges should be used and means should be ignored in further post processing.

The used method should be clearly reported along with the used parameters including:

- reference to the applied rainflow cycle counting method;
- number of used range bins;
- use and value of minimum range threshold.

The number of divisions of the load range should be at least 100 in order to achieve sufficient resolution. Remaining half cycles should be counted as 0,5.

10.7 Cumulative rainflow spectrum

The rainflow cycle counts of individual 10-min records should be assembled to form a single cumulative rainflow spectrum for power production for each load quantity. Other intervals than 10 min can be used. The cumulative rainflow spectrum is determined by summing all the individual rain flow cycle counts of each file in the power production capture matrix. This spectrum is not intended to estimate the fatigue life of the MEC, thus no current speed or turbulence weighting is applied, nor is the design life of the MEC used.

10.8 Damage equivalent load (DEL)

The damage equivalent load (DEL) 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:

$$N = C \cdot S^{-m} \tag{3}$$

where

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

C and m are material properties.

The S-N-curve slope, m, should represent the relevant materials, for example, values of 3 or 5 for welded steel, 6 or 8 for nodular cast iron, and 10 or 12 for glass fibre-reinforced plastic. For example, the 1 Hz damage equivalent load for a 10-min time series is defined by the expression:

$$R_{\text{eq}} = \left(\sum R_i{}^m \cdot n_i / 600\right)^{1/m} \tag{4}$$

where

R_{eq} is the 1 Hz 10-min damage equivalent load;

R_i is the load of the i^{th} range bin of the fatigue load spectrum;

n_i is the number of cycles in the i^{th} range bin of the fatigue load spectrum;

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

10.9 Current speed or wave energy flux binning

Statistical data may be further processed by applying the "method of bins", using for example 0,1 m/s current speed bins and by calculation of the mean values of the current speed and the mean values of the parameters in question for each current speed bin according to the formulas:

$$v_i = \frac{1}{N_i}\sum_{j=1}^{N_i} v_{i,j}$$

$$x_i = \frac{1}{N_i}\sum_{j=1}^{N_i} x_{i,j} \tag{5}$$

where

v_i is the bin averaged current speed in current speed bin i;

$v_{i,j}$ is the 10-min averaged current speed of data set j in current speed bin i;

x_i is the bin averaged variable in question in current speed bin i;

$x_{i,j}$ is the 10-min averaged variable of data set j in current speed bin i;

N_i is the number of 10 min data sets in current speed bin i.

The standard deviation of the means is calculated by:

$$\sigma_{x_i} = \sqrt{\frac{1}{N_i}\sum_{j=1}^{N_i}\left(x_{i,j} - x_i\right)^2} \tag{6}$$

where

σ_{xi} is the standard deviation of the mean in current speed bin i.

The minimum of minimums is calculated by taking the lowest 10-min minimum of all data sets in the bin.

The maximum of maximums is calculated by taking the highest 10-min maximum of all data sets in the bin. A comparable method may be used for wave energy flux binning.

10.10 Power spectral density (PSD)

PSD calculations should be performed on the load quantities in Table 9 or Table 12 for the dynamic measurement load cases. The following information on the analysis should be reported:

- reference to the PSD algorithm used;
- frequency resolution;
- number of lines in the spectrum;
- windowing type;
- length of applied window;
- averaging and/or overlapping.

11 Uncertainty estimation

The uncertainties for all reported quantities should be evaluated and reported. The uncertainty evaluation should consider all relevant sources of uncertainty which occur in the measurement results.

Through the technology qualification process of 5.3, the uncertainty estimation can be adapted to the specific MEC.

Depending on the considered signal, uncertainties can be introduced by the sensor itself, installation effects, calibration, signal conditioning, data acquisition system, or other sources.

Attention should be paid to calculated channels which combine multiple signals. Here all associated signals should be taken into account and their combined uncertainty should be considered.

Guidance on uncertainties is provided in informative Annex E.

12 Reporting

The results of the mechanical loads test should be reported in a report containing the following information:

Through the technology qualification process of 5.3, the reporting can be adapted to the specific MEC.

a) Introduction including:
   1) test objective;
   2) test period.

b) An identification and description of the specific MEC configuration under test, including:
   1) MEC make, type, serial number, production year and structural characteristics;
   2) For a MEC with blades connected to a rotor shaft:
      i) rotor diameter;
      ii) rotor speed or rotor speed range;
      iii) if applicable blade data: make, type, serial numbers, number of blades, fixed or variable pitch, and pitch angle(s);
      iv) type of support substructure or tubular column;

3) description of control system (device and software version);
4) photograph of test MEC;
5) any changes made to the test MEC during the test period classified per 6.8.

c) A description of the test site, including:
1) bathymetry of the location;
2) geographical location with sufficiently detailed information to allow the reader to locate the test machine;
3) test site map showing the surrounding area covering a radial distance of at least 20 times the MEC (e.g. rotor) diameter and indicating the topography, location of the MEC, location of oceanographic and meteorological measuring devices, significant obstacles, other MECs and the measurement sector (if applicable);
4) if site calibration is performed, the site calibration results including the limits of the final measurement sector if applicable and the rationale for any changes from the results of the site assessment.

d) Channel list.

e) Coordinate system used for the test.

f) Instrumentation:
1) description of data acquisition system (sample rate, filters, synchronization if applicable);
2) for each channel:
i) details of instrumentation (make, model, serial number);
ii) details on signal conditioning;
iii) for each instrument, its actual location and orientation, mounting details;
iv) the slope, offset, their derivation method and calculation;
v) calibration data (actual measured data or calibration sheet cover page, end to end checks); for loads channels, also the inputs used for the calibration and their sources (e.g. manufacturer or measured);
vi) any changes made to the instrumentation or calibration during the test period covered in the report.

g) Data verification checks per requirements of Clause 9.

h) Data rejection criteria (e.g. measurement sector, MEC status signals) and data classification (criteria for data to go in different capture matrices).

i) Post processing methods, such as:
1) filtering during post processing;
2) despiking;
3) description of calculated channels;
4) rainflow cycle counting method;
5) current speed trend detection method;
6) any additional data treatment.

j) Results: at a minimum the following results should be included in the test report (except where marked as optional):
1) for the test period:
i) plots of oceanographic and meteorological conditions as a function of time (see Table 10);
ii) For TECs and other water current converters: TI as a function of current speed;
iii) For TECs and other water current converters: TI detrended and as-measured as function of current speed (ratio, difference or both);

iv) scatter plot of oceanographic conditions as a function of wave direction (10-min averages, or other intervals if necessary);

a) wave height;

b) wave period;

c) wave energy vertical distribution in case of submerged WECs;

v) scatter plot of oceanographic conditions as a function of current direction (10-min averages, or other intervals if necessary);

a) current speed;

b) TI;

c) current vertical distribution;

2) for the power production steady state MLC (see 6.4.2.2):

i) capture matrix according to IEC TS 62600-100, IEC TS 62600-200 or IEC TS 62600-300;

ii) time series of oceanographic and meteorological quantities (mandatory signals in Table 10), MEC operation quantities (mandatory signals in Table 11 or Table 13) and mandatory loads identified in Table 9 or Table 12;

iii) scatter plots (e.g. 10-min maxima, minima, mean, standard deviation and DEL's (loads only) as a function of mean current speed and sea state) of oceanographic and meteorological conditions (mandatory signals in Table 10), MEC operational data (mandatory signals in Table 11 Table 9 or Table 12), with binned values on top of the scatter plots (mean of means);

iv) frequency spectra indicating the frequencies values of found peaks in the spectrum;

v) cumulative rainflow spectrum for loads in Table 9 or Table 12;

vi) table with mean of means, maximum of 10-min maxima, minimum of 10-min minima and bin averaged damage equivalent loads (e.g. for current speed in 0,1 m/s bins) for all oceanographic signals (mandatory signals in Table 10, all WEC or CEC operation quantities) mandatory signals in Table 11 or Table 13 and all loads quantities (Table 9 or Table 12) (optional);

vii) plots of power production as a function of current speed (CEC) or wave energy flux (WEC) (optional);

viii) items above for any other mandatory signals.

3) for the parked steady state MLC (see 6.4.2.3):

i) capture matrix linking to filenames (see Table 4 or Table 8);

ii) time series for example for yaw misalignment, if applicable;

4) for transient MLCs (see 6.4.3):

i) capture matrices, including reference to the file identifier containing the events (see Table 5 and Table 6);

ii) for one of each type of event: time series of mandatory oceanographic and meteorological, MEC operation quantities, and load quantities identified in Table 9, Table 10,Table 11, Table 12, Table 13 (whichever applicable);

iii) table with statistics of each channel during the transient (recommended);

5) for dynamic MLCs (see 6.4.4 or 6.5.2):

i) spectra for each MLC for the targeted load quantities;

6) for abnormal operating condition MLC (see 6.4.5):

i) description of the behaviour of the MEC after switching off the control system;

ii) time series and frequency spectra of mandatory oceanographic and meteorological, MEC operation quantities, and load quantities identified in Table 9, Table 10,Table 11, Table 12, Table 13 (whichever applicable and for the operation quantities: whichever is available after switching off the control system);

k) Uncertainty per the requirements of Clause 11:

   1) for measured quantities:

      i) a table of values of the uncertainty sources that were used in the estimation of the total standard uncertainty of the quantity (for guidance see Annex E);

      ii) a statement of the total standard uncertainty of the measured quantity (percentage and constant);

   2) for binned results:

      i) a table with the total standard uncertainty for the bin-averaged value of the measured quantity as a function of bin-average current speed or sea state;

      ii) a table with the total standard uncertainty for the bin-averaged value of the DEL of the measured quantity as a function of bin averaged current speed of sea state;

   3) for damage equivalent loads and cumulative rainflow spectra:

      i) the statement of the total standard uncertainty of the 10-min DEL for the measured quantity (percentage only);

      ii) uncertainty of the cumulative rainflow spectrum (percentage on the ranges).

l) Deviations from the Technical Specification.

m) References.

It is recommended that the information from items d), e) and f) are made available early in the measurement campaign as an instrumentation and calibration report. See Annex F for guidance on reporting methods.

Annex A
(normative)

Full-scale structural laboratory testing of rotor blades

A.1 General

This annex provides specifications for the laboratory testing of WEC or CEC rotor blades. This annex focuses on aspects of testing related to an evaluation of the structural integrity of the rotor blade. The purpose of the tests is to confirm to an acceptable level of probability that the whole installed production of a blade type fulfils the design assumptions. Rotor blades shall be tested as specified. All the tests in this annex can be performed in a laboratory.

The following tests are considered in this annex:

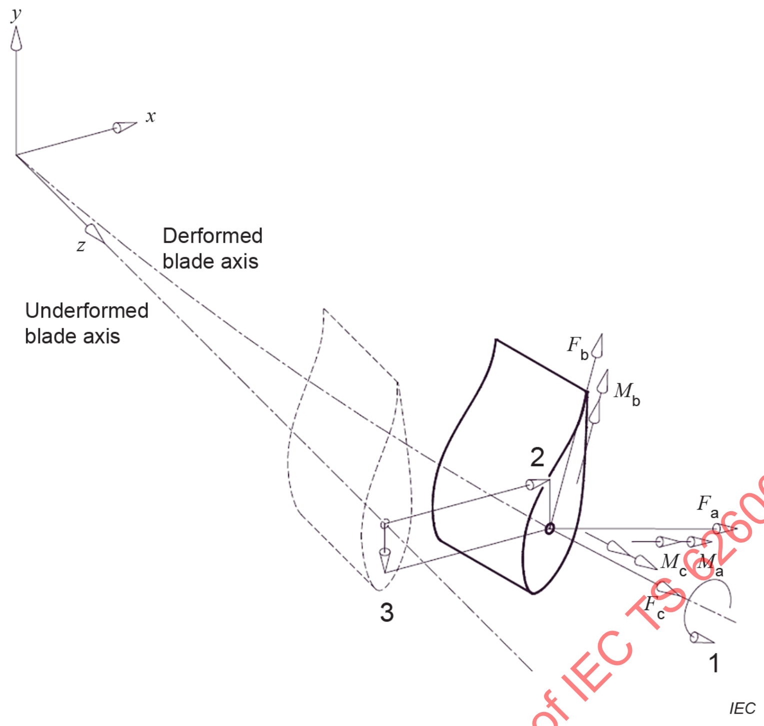
– static load tests;
– fatigue tests;
– static load tests after fatigue tests;
– tests determining other blade properties.

Through the technology qualification process of 5.3, the full-scale structural testing of rotor blades can be adapted to the specific MEC.

NOTE The rotor blades of MECs are much shorter and stiffer than typical wind turbine blades due to the higher power density of the marine environment compared to wind. This also leads to differences in testing methods. The yokes or saddles that introduce the loading to the blade may artificially stiffen the blade at load application points and take up a relatively larger area of the blade. This reduces the available area of the blade for instrumentation and investigation during structural testing. The shorter blades with greater stiffness also exhibit higher natural frequencies preventing the application of resonant testing of composite blades due to internal heating within the structure. Hydraulic loading might be necessary and this will lead to higher energy expenses. To keep the testing affordable only a small number of tests are mandatory.

A.2 Coordinate systems

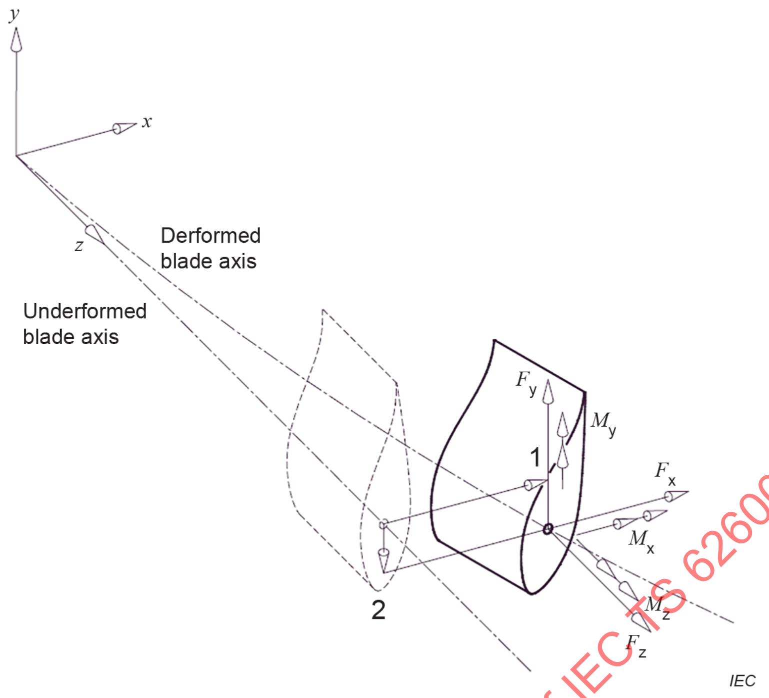
Two different coordinate systems may be used for reference during structural testing. The first, shown in Figure A.1, references the local blade chord directions. The second, shown in Figure A.2, references the global rotor plane directions.



Key

1	Torsion angle
2	Flapwise translation
3	Lead-lag translation
F_a	Flatwise shear force
F_b	Edgewise shear force
F_c	Axial force
M_a	Edgewise bending moment
M_b	Flatwise bending moment
M_c	Torsion moment
	Loads are along and perpendicular to the local blade chord directions

Figure A.1 – Chordwise (flatwise, edgewise) coordinate system



1 Flapwise translation

2 Lead-lag translation

F_x Flapwise shear force

F_y Lead-lag shear force

F_z Spanwise force

M_x Lead-lag bending moment

M_y Flapwise bending moment

M_z Torsion moment

Loads are along the rotor plane reference directions

Figure A.2 – Rotor (flapwise, lead-lag) coordinate system

A.3 General principles

A.3.1 Purpose of tests

The fundamental purpose of a MEC blade test is to demonstrate to a reasonable level of certainty that a blade type, when manufactured according to a certain set of specifications, has the prescribed reliability with reference to specific limit states, or, more precisely, to verify that the specified limit states are not reached and the whole population of blades therefore possess the load carrying capability and service life provided for in the design.

Additionally, tests determining blade properties should be performed in order to validate some vital design assumptions used as inputs for the design load calculations. It has to be pointed out that the required blade property tests do not cover all design assumptions.

Normally, the full-scale laboratory tests dealt with in this annex are tests on a limited number of samples; only one or two blades of a given design are tested, so no statistical distribution of production blade load carrying capability can be obtained. Although the tests do give information valid for the blade type, they cannot replace either a rigorous design process or the quality system for series blade production. Furthermore, the tests described in this annex are not intended to be used for the testing of mechanism functions nor to establish basic material strength or fatigue design data for blades and/or components (see IEC TS 62600-2 for MEC design).

A.3.2 Limit states

To establish and evaluate the test load, a certain amount of information about the design should be known. Usually the blades are designed according to a standard or code of practice such as IEC TS 62600-2 defining the limit states and partial safety factors, which have to be applied to obtain the corresponding design values. The partial safety factors reflect uncertainties and are chosen in order to keep the probability of a limit state being reached below a certain value prescribed for the structure. According to this, a blade should pass the test if the limit state is not reached when the blade is exposed to the test load, representative of the design load.

The basis for establishing the test loads is the entire envelope of blade design loads, derived according to IEC TS 62600-2 or equivalent. The representative test load can be higher than the design load to account for other influences, for example, environmental effects, test uncertainties, and variations in production (see Clause A.7).

The determination of the actual margins to the limit states might be desirable because such margins can provide a measure of the actual safety factors obtained for the resistance of the test blade. However, interpretation of such values is not straightforward and probabilistic methods have to be applied. In this annex, only the ultimate limit state and fatigue limit state are dealt with.

A.3.3 Practical constraints

The practical execution of the tests is subject to many constraints of a technical and economic nature. Some of the most important are listed below:

- the distributed load on the blade can be simulated only approximately;
- the time available for testing is generally one year or less;
- only one or a small number of blades can be tested;
- certain failures are difficult to detect.

The test will be a compromise because these constraints should be dealt with in such a way that the final test results can be used for evaluation of the defined limit states.

As regards the interpretation of the results, it should be borne in mind that the blade used for testing will normally be one of the first blades from series production which will be subject to evolutionary modifications. Even minor modifications could compromise the validity of the tests.

A.3.4 Results of test

The design loads form the basis of the test loading. According to the design calculation, the blade shall be able to survive the design loading. In these design calculations, a number of assumptions are implicitly being made:

- the stresses or strains are calculated accurately or conservatively estimated;
- the classifications of strength and fatigue resistance of all relevant materials and details are estimated accurately or conservatively;
- the strength and fatigue formulations used to calculate the strength are accurate or conservative;
- the production is according to the design.

In the case in which a full-scale test is used as final design verification, the validity of the assumptions mentioned above are checked simultaneously. When a blade fails during testing, at least one of these assumptions has been violated, although without further analysis it might not be clear what caused this unexpected failure.

If no discernible damage to the blade has occurred during the test and the blade structure and the test loading has been evaluated correctly, this gives a strong indication that the blade design will fulfil its requirements. It should be noted that the blade property tests make it possible to check some of the main design assumptions used for the design calculations.

A.4 Documentation and procedures for test blade

The blade manufacturer shall record traceable documentary evidence for the design and construction of the test blade. The records should cover:

- unique identification;
- relevant drawings and specifications;
- lamination plans (for composite blades) and work instructions;
- listing of manufacturer, type and identification number for all important materials used;
- supplier's certificate and blade manufacturers laboratory acceptance report for all important materials used;
- curing history thermographs for thermosetting resins and adhesives at critical locations;
- differential scanning calorimetry or other control of curing;
- manufacturing quality record sheets signed by responsible person;
- weight and balance report detailing total mass and centre of gravity. This report should include information about any loose items fitted during weighing, e.g., root joint elements;
- relevant reports on manufacturing deviations.

Repairs should also be documented. The records should cover the above list. Repairs may be:

- representative examples for repair procedures for manufacturing defects and in-service damage that are qualified with the test blade;
- repairs performed due to damage caused by test loads higher than the target loads.

Special blade modifications can be present for test purposes. During the fatigue tests the loads may have to be magnified to complete the test within an acceptable time-frame. In some cases, the required magnification of the fatigue loads may lead to failure of areas not considered to be tested. In these cases, special blade modifications can be considered. Modification might also be due to load introduction reinforcements. All special blade modifications should be documented.

A.5 Blade test program

A.5.1 Areas to be tested

No single test can load the whole blade optimally. All critical areas should be loaded at least to the target loads. The following potential critical areas should be considered:

- those parts of the blade where calculations show the smallest safety factors against buckling, strength or fatigue life or the highest uncertainty;
- if there is a hydrodynamic braking device (or another blade system), that part of the blade incorporating this device, particularly where the structure is affected by this device.

For blades that are suspended at a single end near the hub, achieving a proper load distribution in the outermost part of the blade is difficult. In most cases, this is not a major problem since the safety margin in a blade typically increases when approaching the tip.

In case the bolts used for connecting the blade to the hub or blade bearing, form an integrated part of the blade root (e.g. in case of T-bolt connections), full-scale testing of the blade should include the proper blade bolts with the intended pretension.

Flatwise and edgewise tests may be sufficient, but that should be evaluated (see Annex G).

A.5.2 Test program

The test program for a blade type shall be composed of at least the following tests (see Table A.1). The tests concentrate on the blade root, since this is the location with generally the highest loads and the highest stresses and also the highest stress concentrations. When other parts of the blade comply more to A.5.1 then these parts of the blade should also be tested in a comparable way to the tests described in Table A.1.

Table A.1 – Blade test program

Measurement quantities	Level of importance
Blade natural frequency in air	Mandatory before the tests and recommended after each static and fatigue test
Mass and centre of gravity	Mandatory
Static blade root flatwise bending moment (M_b)	Mandatory
Static blade root edgewise bending moment (M_a)	Recommended
Fatigue blade root flatwise bending moment (M_b)	Mandatory
Fatigue blade root edgewise bending moment (M_a)	Recommended
Static post fatigue blade root flatwise bending moment (M_b)	Mandatory
Static post fatigue blade root edgewise bending moment (M_a)	Recommended

The tests should be performed in the order as stated in Table A.1.

It is recommended to test the natural frequency of the blade after each static or fatigue test, because it can give information about internal plastic deformation of the blade.

Testing of other blade properties could be of interest (see A.9.9).

The flatwise and edgewise tests can be exchanged for flapwise and lead-lag tests, if flapwise and lead-lag tests can better fulfil A.5.1. Furthermore, a representative load case applied at the correct vector along the blade may replace both flatwise and edgewise or flapwise and lead-lag.

All tests in a given direction and in a given area of a blade should be performed on the same blade part. The flatwise and edgewise sequence of testing may be performed on two separate blades. However, if an area of the blade is critical due to the combination of flatwise and edgewise loading, then the entire test sequence should be performed on one blade.

MECs vary strongly in their blade design. Most blades are suspended at one end with a single blade root to the hub of a rotor. However, there are also blade designs that are suspended at both ends of the blade. This can for example be the case with the Darrieus type of rotor. For this kind of rotors, the test program should be formulated based on A.5.1.

The test program should include blade inspection (see Clause A.10).

A.6 Test plans

A.6.1 General

Test plans shall be established for all the individual tests in the blade test program. The test plans should include a blade description, specification of loads, conditions and the instrumentation to be applied in the test.

A.6.2 Blade description

The blade description in the test plan should be sufficient to ensure that the blade will fit the test stand and avoid unintended overloading during storage, handling, lifting, mounting and testing in the laboratory.

The following information should be supplied:

- blade geometry (preferably in form of a drawing):
  - blade length;
  - chord and twist distribution;
  - pre-bend or sweep;
- mass and centre of gravity;
- blade surface condition;
- blade mounting details:
  - bolt pattern (including tolerances) and interface dimension;
  - bolt size, type and grade;
  - bolt clamping length;
  - bolt pretension or torque procedure;
- lifting and handling procedures;
- maximum expected deflections under load;
- profile geometry at load introduction points.

Additional information (such as the stiffness of the mounting structure) may be required depending on the test specifics.

A.6.3 Loads and conditions

The test plan should include the target loads, test loads, application methods and sequence of the tests to be conducted. Environmental conditions that may affect the execution of the tests should also be given in the test plan (see A.7.4).

A.6.4 Instrumentation

The position and orientation of load cells, strain gauges, deflection transducers and other sensors should be specified in the test plan.

A.6.5 Expected test results

It is recommended that predictions (deflections, strains, etc.) are provided corresponding to all sensor measurements to enable and assist planning, evaluation and quality control.

A.7 Load factors for testing

A.7.1 General

In testing, various load factors should be taken into account. Those arising from the design are discussed in A.7.2 and A.7.3. Apart from these, additional test load factors should be applied to account for effects introduced by the test methodology. These test load factors are discussed in A.7.4.

A.7.2 Partial safety factors used in the design

In the design calculations, partial safety factors (or coefficients) have to be included. According to IEC TS 62600-2, these include:

γ_m: material factors;

γ_f: partial load factors.

In the design calculation, both the partial safety factors (γ_m and γ_f) have to be applied. The product of these partial factors is an important figure for the overall safety level of the design. Both γ_m and γ_f have to be incorporated in the test load. The partial safety factors above should be used for at least one of the two required static tests (pre or post fatigue). For the other static test, the factors can be set to 1,0.

A.7.3 Factors on materials

Material conversion factors take into account specific differences between the conditions of the material in the structure and the conditions for which the strength and fatigue formulation were derived. See IEC TS 62600-2 for the formulation of the material factors. The static and fatigue test loads should include the material factors for manufacturing and for environment. In the case of a composite material these are the factors γ_{m2} and γ_{m3}.

A.7.4 Partial factors on loads

During the design, the partial factors on loads γ_f take into account the uncertainties in the loads-formulation. Therefore, the test blade should be able to resist the design load including the appropriate partial factors for loads. The number of cycles that a MEC turbine blade performs during its design life can vary strongly. The design life load cycles should be calculated including the load variation over the cycles.

If there is no failure probability distribution data available for the particular blade design and particular manufacturing procedure, the following test load factors should be used:

for static tests: γ_{su} = 1,1;

for fatigue tests: γ_{sf} = 1,1.

The static load factor above should be used for at least one of the two required static tests (pre or post fatigue). For the other static test, γ_{su} can be set to 1,0.

The more the fatigue test is accelerated, i.e. the lower the number of cycles in the fatigue test, the larger the uncertainty associated with the conversion from the fatigue design loads to the fatigue test loads. The reduction factor H_r gives the relation between the number of cycles during the service life (n_0) and the number of cycles in the fatigue test (n_{ft}):

$$H_r = \frac{n_0}{n_{ft}} \tag{A.1}$$

where

H_r is the reduction factor;

n_0 is the number of calculated cycles for the design service life;

n_{ft} is the number of cycles in the fatigue test.

The reduction factor H_r should be accounted for by applying the test load factor γ_{ef} to the fatigue design loads. The value of γ_{ef} is given for different values of H_r in Table A.2 (see also Annex I). When a better insight in the specific fatigue process leads to different but well documented values for γ_{ef}, then these values can be used.

Table A.2 – Recommended values for γ_{ef} as a function of the reduction factor H_r

Reduction factor (H_r)	γ_{ef}
100	1,065
50	1,050
20	1,035
10	1,025
5	1,015

The total number of cycles (n_0) during a service life of a TEC and a WEC can differ considerably. For a TEC service life of 20 years the total number of tidal cycles is around 28 000, but there are also higher harmonics in the tides and there can be wave induced cycles, turbulence induced cycles and load cycles on the blades induced by the support structure. The phenomena with the highest frequencies can induce up to around 50 million cycles. For WECs the total number of wave induced cycles (n_0) can be estimated at the same order of magnitude.

In general, the environmental conditions at the test facility are more benign than at the actual operational area, and consequently, design conditions. In many strength and fatigue formulations, the effect of these conditions is expressed by factors. However, it can also result in different strength or fatigue formulations for the different conditions.

When the test environmental conditions are more benign, this leads to a magnification of the required test load. The appropriate factor (γ_{lu}) has to be checked by the evaluation of the test load distribution, but for both conditions the appropriate strength or fatigue formulation has to be applied (see Annex H). Whenever the effect is given by factors, these can be used as an initial estimate for the factor necessary to magnify the load to arrive at an equivalent test load.

A.7.5 Application of load factors to obtain the target load

For the tests, the design load is compiled into a target load. The test load should ideally be equivalent to the target load. The determination of the target loads should be based on appropriate strength and/or fatigue formulations and elastic properties for the materials used in the areas to be tested.

The target load for the static test is defined as:

$$F_{\text{target-u}} = F_{\text{du}} \cdot \gamma_{\text{su}} \cdot \gamma_{\text{lu}} \tag{A.2}$$

where

$F_{\text{target-u}}$ is the target loading;

F_{du} is the design loading (including partial factor for loads γ_f and γ_m (see A.7.2);

γ_{su} is the test load factor for blade to blade variation (see A.7.4);

γ_{lu} is the test load factor for environmental effects, if applicable (see A.7.4).

The target load for the fatigue test is defined as:

$$F_{\text{target-f}} = F_{\text{df}} \cdot \gamma_{\text{sf}} \cdot \gamma_{\text{ef}} \cdot \gamma_{\text{lf}} \tag{A.3}$$

where

$F_{\text{target-f}}$ is the target loading;

F_{df} is the damage equivalent design loading (including partial factor for loads γ_f and γ_m) (see A.7.2);

γ_{sf} is the test load factor for blade to blade variation (see A.7.4);

γ_{ef} is the test load factor for reduction of the test load cycles (see A.7.4);

γ_{lf} is the test load factor for environmental effects, if applicable. Alternatively, the environmental effects can be accounted for in the conversion from design loads to damage equivalent design loads, if applicable (see A.7.4).

The determination of the damage equivalent design loads for fatigue includes appropriate S-N formulation(s), cycle counting procedures, an appropriate damage summation model, R-value effects, i.e. ratio between minimum and maximum value during a load cycle, and all other relevant information.

A.8 Test loading and test load evaluation

A.8.1 General

For each test, the target loads should be defined in the test plan. Sufficient information should be provided to allow the test load to be accurately assessed against the target load. In principle, the six load components should be given, including phase and frequency information required to generate combined load cases. The load components flatwise and edgewise moments are the far most important components. Flatwise and edgewise shear loads will normally implicitly be taken care of because of the moments. Only for more specialized blades will the torsion and lengthwise forces have to be taken into account. The coordinate system relevant for the load components should be clearly specified (see Clause A.2). Effects of changes in load direction should be carefully considered when preparing the test plans and reports, and when estimating uncertainties. It is recommended to monitor the blade displacement and rotation in all six degrees of freedom as well as the loading vector in the x, y and z direction.

Since the test should prove that the blade can survive the target loading, the test loading should be evaluated. It should be checked in which areas of the blade the severity of the test loading is indeed equal to or more severe than the target loading. Because the severity of the test loading compared to the target loading will vary over the blade area, in principle the evaluation has to be done at all locations of the blade area that are to be tested (see also Annex G).

If applicable, loads on critical mechanical and electrical blade subsystems (e.g., hydrodynamic braking subsystem, monitoring subsystem, hydrodynamic control subsystem, etc.) are often different in character from the general loads on the blades and may need extra specification and specific tests. In the case of mechanisms, it is unlikely that sufficient loading conditions will be present in the standard tests to qualify the subsystem integrity. Additional testing may be necessary to simulate special loading cases, including torsion and radial loading. For systems whose failure may result in unsafe operation of the MEC, special consideration should be given to verify the appropriate level of structural integrity. The accumulated damage should not cause functional failure of these subsystems. Loads for testing of blade subsystems are not covered further in this document.

A.8.2 Influence of load introduction

In the case where the test load is introduced as concentrated forces at a restricted number of locations (e.g. at actuator positions), the sections where the load is applied are disturbed and may be strengthened over a certain area by the load introduction fixtures. Therefore, at these areas the blade may not be properly tested and should not be considered in the analysis or evaluation. The length (in the longitudinal direction) of the disturbed area can be estimated from calculations or measurements.

Without further analysis, it could be assumed that this affected area might extend as much as three quarters of the chord length on either side of the fixture. In yoke or saddle design, special attention should be given to buckling sensitive areas (e.g. trailing edge in compression).

Also, if special modifications are made for test purposes (see Clause A.4) the above-mentioned considerations are relevant.

In general, MEC blades are relatively stiff and the maximum loading does not lead to large deflections that influence the load direction. However, with some slender blade designs, larger deflections might influence the load direction. The finite distance between attachment points for an actuator system in the laboratory and on the blade-yoke implies that load direction angles will change when loading these slender blades. A longer distance normally reduces this change. The change in angle will result in a change to the load direction relative to the blade axis and the moment arm for calculation of the applied root moment and thereby also the moment at any point between the root and the load application point.

In the case of a single axial load with the deformation perpendicular to the load, such as when the load is applied in the lead-lag direction and the blade also deforms in the flap direction, changes in the load direction may also occur. Yokes not loaded perpendicular to the blade axis at high load may slip due to tangential forces. Such loading of yokes may also result in local prying forces that unintentionally overload the blade structure.

Multiple load introduction points could be used to minimize adverse loading conditions, especially at the higher load levels. Care should also be taken to space yokes away from critical areas to be tested so that they are neither supported nor adversely influenced by the load introduction fixtures.

A.8.3 Static load testing

In static load testing, the area to be tested should be loaded to each of its most severe design load conditions while taking into account the variations in a population of manufactured blades and differences between the laboratory and the design environmental conditions (see A.7.4).

If different load distributions or orientations are needed to represent the different extreme load cases in the areas to be tested, each of these should be applied.

It should be noted that the blade may be most vulnerable to certain failure modes when a resultant load, which is not necessarily the highest in magnitude, is appropriately applied in a particular direction.

For each load, the blade shall withstand the maximum load for the specified load duration. Since most common blade materials exhibit a reduction of strength with duration of load, the duration of the test load should be at least as long as the peak design load. If the design load information provides a well-defined duration for the peak load on the blade, the test load and duration should be based directly on that. If no duration of constant test load is stated, then 30 s should be the minimum value. For TECs the recommended minimum duration of the test load is 6 h, about equivalent to half of a single tidal cycle in a diurnal tidal pattern.

In general, all locations will be regarded as sufficiently tested if the loading during the static load test is equal to or higher than the target load. In case of failures caused by loads higher than target loads, repair is allowed before a fatigue test.

If the blade is tested with combined loading, it is not intended to combine maximum load in one direction with maximum load in the other direction. Instead, the maximum load in one direction should be combined with an appropriate load in the other direction. Ideally the actuators are aligned to deliver the correct test load vectors.

At least one actuator should be used that is capable of applying the test load in the x and y direction.

A.8.4 Fatigue load testing

On the areas to be tested, a test loading has to be generated giving a fatigue damage equivalent to the fatigue damage caused by the target loads. The fatigue test loads will generally be chosen in such a way that, for practical reasons, the test time is reduced. To test areas around the whole blade cross-section, various combinations of flatwise and edgewise loading may be employed.

To reduce the number of cycles during the test, the load normally has to be increased to obtain a reasonable compromise between testing as realistically as possible and obtaining a more reasonable testing time.

The magnification should lead to the appropriate theoretical equivalent fatigue damage accumulation, having the following limitations in mind:

- the maximum values of the stresses or strains might surpass the static strength of the material and consequently lead to static damage or failure;
- the stresses or strains may be so high that the usual assumption of the linearity between forces and stresses no longer applies, such as in the case of buckling;
- internal heating of the highly stressed areas.

Especially in the case of variable amplitude loading, these limits can be reached at a relatively low load magnification factor. In that case, only the intermediate load cycles can be increased further, and the test loading becomes more and more a constant-amplitude loading as a consequence.

The mean loads applied during fatigue testing should be as close as possible to the mean load at the operating conditions that are most severe to the fatigue strength.

Locations will be regarded as sufficiently tested if the theoretical damage (e.g. Miner summation) during the fatigue test is equal to or higher than the theoretical damage based on the target load.

The theoretical test damage can be evaluated by accumulation of the damage from all partial tests.

When a certain area of the blade fails after it has been subjected to theoretical damage due to the test load that is equivalent to or higher than the damage due to the target load, that area has passed the test. In principle, testing of the blade can continue to reach equal severity for the other areas. This is only valid for the areas that are not affected by stress redistribution due to the damage.

In case of failures caused by loads higher than target loads, repair is allowed. The consequences of any repairs should be evaluated.

At least one actuator should be used that is capable of applying the test load in the x and y direction.

A.9 Test requirements

A.9.1 Test records

All test activities shall be noted in a log.

A.9.2 Instrumentation calibration

All instrumentation used to collect data for evaluation of test results should be calibrated. In the case of applied sensors and gauges that cannot be independently calibrated, specifications should be traceable and the remaining chain should be calibrated. Procedures for controlling, calibrating, maintaining and inspecting measuring and test equipment should be developed and implemented in accordance with ISO/IEC 17025 or equivalent. When possible, an end-to-end calibration of the system should be made, verifying performance of all system components. In the procedures, it should be addressed that recalibration has to be done for sensors that might be damaged as a consequence of a catastrophic blade or equipment failure during testing.

During the loading of rotor blades internal parts like the shear webs, might deform plastically and this might change the relationship between the measured strain and the calculated loading. It is therefore recommended to perform the calibration of this relationship before and after the loading, in these cases where a plastic deformation can be expected. It is also recommended to report the measured strain separate from the calculated stress, forces or bending moments.

A.9.3 Measurement uncertainties

All device uncertainties should be listed in the test report.

In addition, the following uncertainties should be estimated and reported:

- uncertainties in magnitude, direction and location of any applied load;
- uncertainties in magnitude, direction and location of displacement;
- uncertainties in magnitude, direction and location of the measured strain.

A.9.4 Root fixture and test stand requirements

In case the root area and fixture are considered for testing, deviations between the test stand and the MEC blade assembly should be evaluated.

The measured deflection of the blade should be corrected for deformation of the blade root fixture and the test stand. For the measured natural frequencies, damping and mode shapes, the effect of the test stand should be considered. For relatively rigid test stands (contribution to tip deflection less than 1 %), the effect of the test stand can be ignored, provided sufficient measurements have previously been carried out to document this claim.

A.9.5 Environmental conditions monitoring

Environmental records may be necessary to quantify effects on the test blade such as stiffness variations, strain gauge drift (particularly on single element bridges) or drift in other sensors.

As a minimum, the temperature should be recorded at the blade (inside or outside; whichever is possible) to evaluate the difference between ambient temperature and blade temperature. These records should be kept at time intervals sufficient to monitor fluctuations during all tests.

For materials influenced by moisture, the ambient humidity should be recorded at intervals sufficient to monitor fluctuations during the test.

A.9.6 Deterministic corrections

The test may be influenced by gravitational loads that are not part of the test load or measured by the instrumentation. These tare loads should be properly accounted for during the test and processing of the test data. Tare loads can result from the masses of:

- the blade itself;
- load introduction fixtures (actuators, whiffletree apparatus, clamping structures, etc.);
- cables, slings, and transducers;
- system damping.

Tare loads and their location with respect to the blade coordinate system should be documented.

As the blade deflects, the load direction relative to the blade orientation can change. These load direction changes should be taken into account.

Loads not acting through the elastic axis either due to deflection, pre-bending or test set-up will cause torsion moments in the blade. These moments can be significant and should be considered when specifying the test load. The applied loads may be intentionally offset from the elastic axis to give a prescribed torsion moment. The elastic axis is the imaginary line, lengthwise of the blade, along which transverse loads are applied in order to produce bending only, with no torsion at any section.

A.9.7 Static test

Testing using static loads is undertaken to obtain two separate types of information. One set of information relates to the blade's ability to resist the loads that the blade has been designed for. The second set of information relates to blade properties, strains and deflections arising from the applied loads. For convenience, the two sets of information are usually obtained during the same static test, although this is not a requirement.

During the static load tests the following should be measured (or derived from measurement) and recorded:

- magnitude and direction of the applied load(s) at the load levels where strains are measured;
- a time signal – to assure minimal time at a load level (see A.8.3). This can be in the form of an actual time signal or can be derived from the sample rate.

The strains in the rotor blade should be measured in areas of interest. Strain gauges are the preferred device used for these measurements. Depending on the areas of interest, strains in one or more directions should be measured. For composite rotor blades the strains at the following areas of interest should be measured:

- the main load carrying structure (e.g. spar cap, beam flange) in the upper and lower shell, at four cross sections distributed over the area to be tested. The direction of strain measurement is typically longitudinal to the blade spanwise axis, but can be in other directions as required by model verification;

- the trailing and leading edges at the position of the maximum chord length and at a quarter of the blade length measured from the blade root. The direction of strain measurement is typically parallel to the edges of the blade, but can be in other directions as required by model verification;
- the composite webs at the blade root area and on a web section with high calculated strain. Shear strain is the important strain measurement required and typically strain gauge rosettes are used;
- the two highest loaded connecting bolts, if the bolts are an integral part of the area to be tested, then bolt tension should be measured.

For steel or other metal rotor blades the strain should be measured at comparable locations at the outside of the blade.

Other areas of interest for strain measurements are typically at blade locations in which geometry transitions and critical design details are present, or the strain level is expected to be high.

The location and the orientation of the individual strain measurements should be accurately documented. Strain measurements should be taken for at least five load levels, distributed over the load range used in the test.

Deflection should be measured at a number of points adequate to determine the deflection of the blade, but at not less than two locations along the blade.

The deflection on the test rig should be monitored to understand the apparent deflection of the blade due to the test fixture deflection and bending.

A.9.8 Fatigue test

During the fatigue tests the following should be measured and recorded:

- cycle count;
- signals that are used to control the blade test (for example: applied loads, deflections, acceleration, strains).

The functionality of the sensors should be verified throughout the test. If a sensor or instrument fails during the fatigue test, its criticality for the test should be assessed. Those that are critical to the fatigue test should be fixed or replaced. To prove that the assumptions for the fatigue test are still valid, the stiffness of the blade should be checked and documented several times (e.g. 5) throughout the test.

A.9.9 Other blade property tests

The blade mass and the spanwise location of the centre of gravity should be determined. Subcomponents included (e.g. root bolts) should be stated.

As a minimum the first flatwise frequency should be measured. The mass of the test instrumentation can influence the results of the natural frequency tests.

Testing of other blade properties may be of interest. These may include (but are not limited to):

- damping;
- mode shapes;
- creep;
- mass distribution;
- stiffness distribution.

A.10 Test results evaluation

A.10.1 General

Before starting the test program, after each test and at frequent intervals during the fatigue test, the outside of the blade should be visually inspected.

Infrared or ultrasonic inspection and recording of sound emission may be used to supplement the visual inspection.

Inspection results should be documented in a log. Observations should be accompanied by appropriate documentation.

If applicable, critical electrical mounted or imbedded systems should be inspected and checked for proper function periodically throughout the test program.

Irreversible property changes of the blade are considered as damage. The following types of damage are defined:

- damage in the form of catastrophic failure of the test blade;
- damage in the form of permanent deformation, loss of stiffness or change in other blade properties;
- superficial damage.

Observed damage should be considered by the designer in a failure evaluation (see A.10.5). For detailed investigations after the test, the blade may be sectioned.

A.10.2 Catastrophic failure

Catastrophic failure is disintegration or collapse of a component or the complete test blade. Catastrophic failure results in loss of vital function which impairs safety. The following observations can be considered as catastrophic failure:

- breaking or collapse of the primary blade structure;
- complete failure of structural elements such as internal or external bond lines, skins, shear webs, root fasteners, etc.;
- major parts become separated from the main structure.

Catastrophic failure is normally readily observed.

Observations should be documented by description in writing and recording in the form of photographs and/or videos.

A.10.3 Permanent deformation, loss of stiffness or change in other blade properties

The mass, centre of gravity and natural frequencies measured before the static test (see A.5.2, and A.9.9) should be evaluated against the design assumptions. Other measured blade properties as described in A.9.7 (strain distribution and deflection) should be evaluated both after the static test and after the post fatigue static test.

The measurement of loads, deflections, strains and/or natural frequencies according to A.9.7 and A.9.9 should be evaluated to detect possible loss of stiffness and/or permanent deformation.

A.10.4 Superficial damage

Marking of time and extent of damage on the blade surface should be used for reference when observing progress of damage throughout the test program.

The following examples of observations can be considered as superficial damages:

- small cracks in laminate or bond lines of composite blades;
- gelcoat cracking;
- paint flaking;
- surface bubbles;
- minor panel buckling without permanent deformation or damage;
- small delaminations of composite blades.

In case repair of any of the superficial damages is described in the operation and maintenance manual for the blade type, these damages are allowed to be repaired during the testing. For example, that could be the case for small cracks in laminate or bond lines, gelcoat cracks or paint flaking. If repairs are carried out, they have to be documented according to Clause A.4.

A.10.5 Failure evaluation

Damage in the form of permanent deformation or loss of stiffness can be catastrophic or lead to functional failure for a blade in service.

Superficial damage can develop into functional or catastrophic failure over time in environmental conditions experienced by blades in service.

The designer should evaluate the damages observed during the initial static tests and the fatigue tests and determine the effect on safety against catastrophic or functional failure. The basis for this evaluation is not covered by this present technical specification.

A.11 Renewed testing

Due to adjustments in the production, improvements in designs and optimisations in general, the production rotor blades will often deviate from the blade that was originally used for full-scale testing.

Since it is impractical to repeat the full-scale test every time adjustments and improvements are made, it is necessary to make a distinction between changes requiring or not requiring a renewed full-scale test. While such requirements are outside the scope of this Technical Specification and are left to the judgment of the manufacturer and/or certification body, some considerations are given below.

Observations made from the previous full-scale test should be considered, since these may indicate the correctness of the design assumptions and be valuable in assessing the need for retesting. Given the level of change, needs for renewed full-scale testing may only comprise a limited full-scale test, e.g. static test only, fatigue test only, test in one direction only, etc.

In general, adjustments and improvements that obviously strengthen the blade tend to reduce the need for renewed full-scale testing. Furthermore, changes only affecting areas with large safety margins should be less prone to trigger the need for renewed full-scale testing. However, changes that influence the loading of the MEC turbine and thereby influence the design assumptions for the blade should be considered.

Some examples of adjustments and improvements in production and design typically requiring, or not requiring, renewed full-scale testing are given in Table A.3.

Table A.3 – Examples of situations typically requiring or not requiring renewed testing

Adjustments and improvements typically requiring renewed full-scale testing	Adjustments and improvements typically not requiring renewed full-scale testing
Modified profile shape around significant tested areas (for example, largest chord)	Modified blade tip shape
Shortening of some layers of fibres	Prolongation on some layers of fibres
Shift to a new type of resin or new type of fibres (e.g. shift from polyester to epoxy or from glass fibres to carbon fibres)	Minor adjustments in raw materials as a part of the continuous development by the material supplier or shift to a new supplier of identical materials. In the latter case testing on coupon level may be needed
Shift to a new type of core material with different Young or shear modulus in sandwich constructions. (Often combined with a change in core material thickness)	Modification of the chamfer angle in some core materials in sandwich construction.
Major changes in stacking sequences in sandwich constructions	Minor changes in stacking sequences in massive laminates
Shift to a new production method (e.g. hand lay-up to injection)	Minor changes in the production process (e.g. adjustments on curing cycle)

Besides adjustments and changes to the blade structure, it may be the case that the design loads for a certain blade change after the full-scale test of the blade has been completed. In this case, renewed full-scale testing will only be needed if the design loads increase. When the design loads change, a new evaluation of the test loads against the design loads should be conducted.

A.12 Reporting

A.12.1 General

The tests shall be documented in a report containing enough information to make the tests and their results comprehensible.

A.12.2 Test report content

The test report(s) should include the following items, depending on the type of test:

- table of contents;
- contractor for the test;
- dates and locations for the tests;
- blade identification;
- blade description;
- test set-up and procedures;
- description of test load;
- test equipment used (including make, model, serial numbers, etc.);
- reference to calibration records of measurement equipment;
- locations of sensors and measurement points;
- blade specific calibration details (tare loads, strains, etc.);
- estimated uncertainties;
- description of inspections, repairs and observations;
- summary of tests and test results;
- deviations from test plans, laboratory procedures or normative references;
- list of references (test plans, laboratory procedures, normative references).

A.12.3 Evaluation of test in relation to design requirements

The evaluation of the test in relation to the design requirements should at least include:

- evaluation of test loads including test load distribution;
- evaluation test results with respect to the DLCs (IEC TS 62600-2);
- evaluation of blade stiffness.

Annex B
(informative)

Example coordinate systems for MECs with blades connected to a rotor shaft

B.1 General

This informative annex gives an example of a coordinate system for MECs with blades connected to a rotor shaft that are supported by a tubular column to the seabed or riverbed, or to a floating device. All coordinate systems are right-handed Cartesian systems.

B.2 Blade coordinate system

The blade coordinate system is fixed to the blade. In general, its origin is the centre of the blade flange (see Figure B.1).

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.

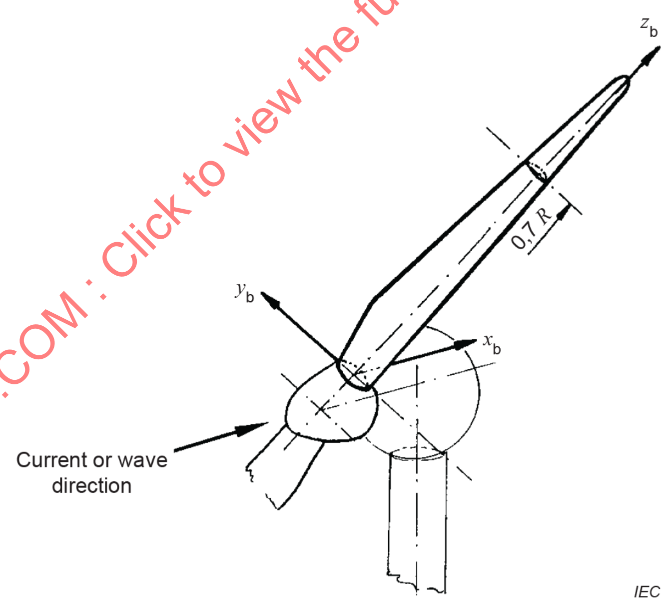


Figure B.1 – Blade coordinate system

B.3 Hub coordinate system

To transform the blade coordinates into the hub coordinate 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 coordinate system rotates with the main rotor shaft. The origin is on the main shaft in the plane perpendicular to the main shaft that contains the blade coordinate origin of the reference blade (see Figure B.2).

x_h-axis Parallel to the main shaft, positive in the current or wave 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.

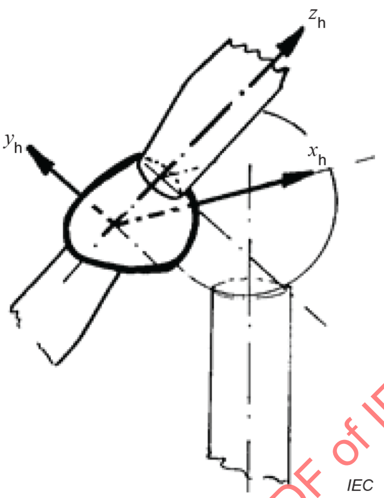


Figure B.2 – Hub coordinate system

B.4 Nacelle coordinate system

When transforming the hub coordinates into the nacelle coordinate 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 coordinate system has its origin on the yaw axis at the closest point to the main shaft centre axis (see Figure B.3).

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 coordinate system yaws with the nacelle.

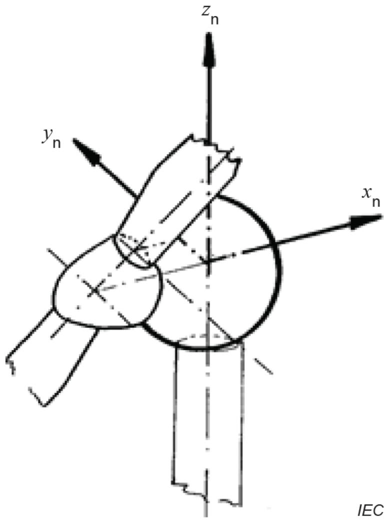


Figure B.3 – Nacelle coordinate system

B.5 Tubular column coordinate system

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

The tubular column coordinate system has its origin at the centre of the tubular column base (see Figure B.4).

z_t-axis	Co-axial with the tubular column axis.
x_t-axis	To be defined as convenient (i.e. according to the site and the shape of the tubular column cross-section).
y_t-axis	Defined by right-hand system of z_t and x_t.

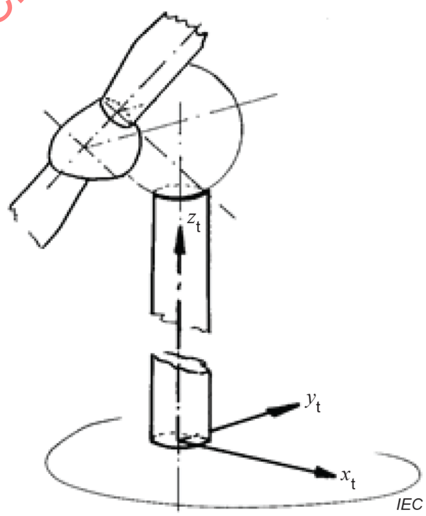
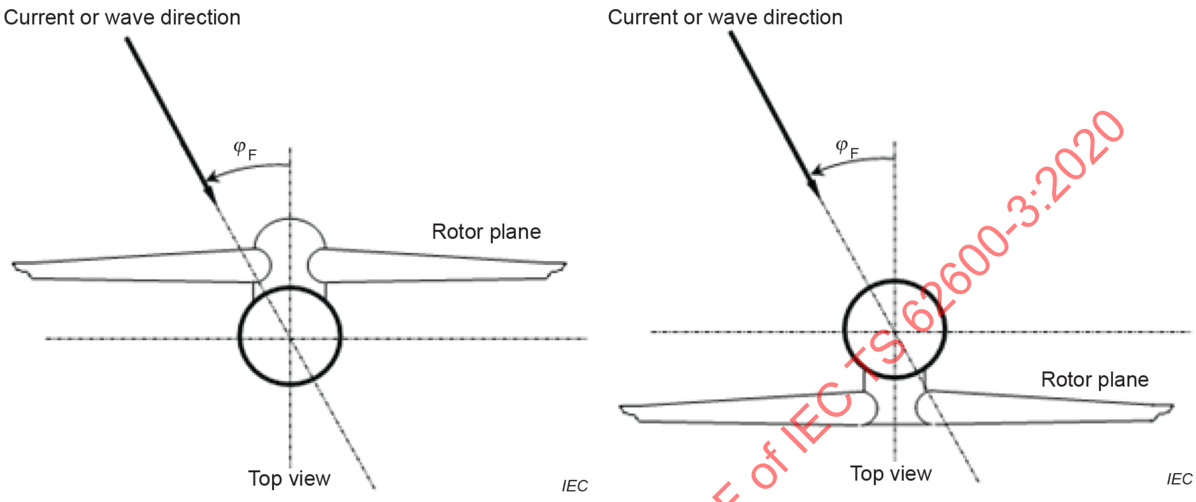


Figure B.4 – Tubular column coordinate system

B.6 Yaw misalignment

The yaw misalignment is defined as the angle between the horizontal projections of the centre line of the rotor shaft and of the current or wave direction. It is defined as the yaw position minus current or wave direction.

In Figure B.5, the yaw misalignment is shown to be positive.



a) Rotor directed towards the current or waves **b) Rotor directed from the current or waves**

Figure B.5 – Yaw misalignment

B.7 Cone angle and tilt angle

The cone angle and tilt angle are shown in Figure B.6.

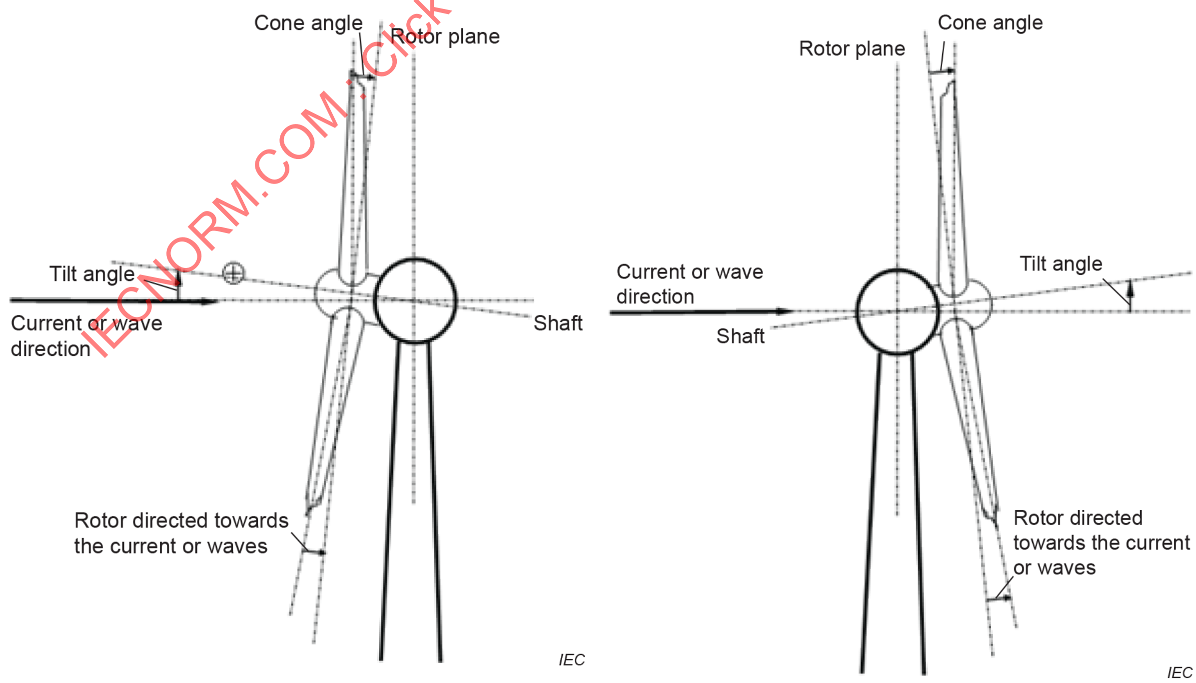


Figure B.6 – Cone angle and tilt angle