BS EN ISO 19901-7:2013

BSI Standards Publication

Petroleum and natural gas industries — Specific requirements for offshore structures

Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units

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National foreword

This British Standard is the UK implementation of EN ISO 19901-7:2013. It supersedes BS EN ISO 19901-7:2005 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee B/525/12, Design of offshore structures.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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English Version

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Industries du pétrole et du gaz naturel - Exigences spécifiques relatives aux structures en mer - Partie 7: Systèmes de maintien en position des structures en mer flottantes et des unités mobiles en mer (ISO 19901-7:2013)

Erdöl- und Erdgasindustrie - Spezielle Anforderungen an Offshore-Anlagen - Teil 7: Betriebssysteme für das Positionshalten schwimmender Anlagen und mobiler Offshore-Einheiten (ISO 19901-7:2013)

This European Standard was approved by CEN on 5 January 2013.

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Foreword

This document (EN ISO 19901-7:2013) has been prepared by Technical Committee ISO/TC 67 "Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries" in collaboration with Technical Committee CEN/TC 12 “Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries” the secretariat of which is held by AFNOR.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by November 2013, and conflicting national standards shall be withdrawn at the latest by November 2013.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

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Endorsement notice

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 19901-7 was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, Subcommittee SC 7, *Offshore structures*.

This second edition cancels and replaces the first edition (ISO 19901-7:2005), which has been technically revised.

This second edition of ISO 19901-7 includes several major additions and changes, primarily to Annex A (informative). The largest change is the addition of detailed informative text incorporated directly from API RP 2SK on all types of anchor design. In the first edition of this International Standard, this material was previously addressed only by reference to API RP 2SK. Informative material has also been added from API RP 2SK regarding the analysis and mitigation of vortex-induced motions of large cylindrical hulls. Consequently, the normative text has been modified to remove reference to API RP 2SK and to cross-reference portions of the expanded informative annex.

The other significant change is the updating of guidance on polyester rope mooring design to conform to the provisions of the recent amendment to API RP 2SM. The changes include new definitions of stiffness, recognition of effective filter barriers, removal of the prohibition against the rope touching the sea floor, and more detail on minimum tension requirements, among others. Additionally, minor corrections were made to the text in 7.4.4 (Wind actions) and 8.3.4 (Riser considerations), and the terminology "most probable maximum" has been standardized throughout. Finally, the Norwegian clause of Annex B has been updated at the request of Norway, and a new Canadian clause has been added.

ISO 19901 consists of the following parts, under the general title *Petroleum and natural gas industries — Specific requirements for offshore structures*:

— *Part 1: Metocean design and operating considerations*

— *Part 2: Seismic design procedures and criteria*

— *Part 3: Topsides structure*

— *Part 4: Geotechnical and foundation design considerations*

— *Part 5: Weight control during engineering and construction*

— *Part 6: Marine operations*

— *Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units*

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The following parts are under preparation:

— *Part 8: Marine soil investigations*

ISO 19901 is one of a series of International Standards for offshore structures. The full series consists of the following International Standards:

— ISO 19900, *Petroleum and natural gas industries — General requirements for offshore structures*

— ISO 19901 (all parts), *Petroleum and natural gas industries — Specific requirements for offshore structures*

— ISO 19902, *Petroleum and natural gas industries — Fixed steel offshore structures*

— ISO 19903, *Petroleum and natural gas industries — Fixed concrete offshore structures*

— ISO 19904-1, *Petroleum and natural gas industries — Floating offshore structures — Part 1: Monohulls, semi-submersibles and spars*

— ISO 19905-1, *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units — Part 1: Jack-ups*

— ISO/TR 19905-2, *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units — Part 2: Jack-ups commentary and detailed sample calculation*

— ISO 19905-3, *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units — Part 3: Floating units*[1)]

— ISO 19906, *Petroleum and natural gas industries — Arctic offshore structures*

1) Under preparation.

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Introduction

The series of International Standards applicable to types of offshore structure, ISO 19900 to ISO 19906, constitutes a common basis covering those aspects that address design requirements and assessments of all offshore structures used by the petroleum, petrochemical and natural gas industries worldwide. Through their application, the intention is to achieve reliability levels appropriate for manned and unmanned offshore structures, whatever type of structure and nature or combination of materials used.

It is important to recognize that structural integrity is an overall concept comprising models for describing actions, structural analyses, design rules, safety elements, workmanship, quality control procedures and national requirements, all of which are mutually dependent. The modification of one aspect of design in isolation can disturb the balance of reliability inherent in the overall concept or structural system. The implications involved in modifications therefore need to be considered in relation to the overall reliability of all offshore structural systems.

The series of International Standards applicable to types of offshore structure is intended to provide wide latitude in the choice of structural configurations, materials and techniques without hindering innovation. Sound engineering judgement is therefore necessary in the use of these International Standards.

This part of ISO 19901 was developed in response to the worldwide offshore industry's demand for a coherent and consistent definition of methodologies to analyse, design and evaluate stationkeeping systems used for floating production and/or storage platforms of various types (e.g. semi-submersibles, spar platforms, ship-shaped structures) and to assess site-specific applications of mobile offshore units (such as mobile offshore drilling units, pipelay units, construction units).

Stationkeeping is a generic term covering systems for keeping a floating structure, which is under the constant influence of external actions, on a pre-defined location and/or heading with limited excursions. Stationkeeping systems resist external actions by means of any combination of the following:

— mooring systems (e.g. spread moorings or single point moorings);

— dynamic positioning systems (generally consisting of thrusters).

The external actions generally consist of wind, wave, current and ice actions on the floating structure, mooring and/or risers.

Some background to, and guidance on, the use of this part of ISO 19901 is provided in informative Annex A. The clause numbering in Annex A is the same as in the normative text to facilitate cross-referencing.

Regional information, where available, is provided in informative Annex B.

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Petroleum and natural gas industries — Specific requirements for offshore structures —

Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units

1 Scope

This part of ISO 19901 specifies methodologies for

a) the design, analysis and evaluation of stationkeeping systems for floating structures used by the oil and gas industries to support

   1) production,

   2) storage,

   3) drilling, well intervention and production,

   4) production and storage,

   5) drilling, well intervention, production and storage, and

b) the assessment of stationkeeping systems for site-specific applications of mobile offshore units (e.g. mobile offshore drilling units, construction units, and pipelay units).

Most stationkeeping systems used with the class of floating structures covered by a) are termed “permanent mooring systems”, for which this part of ISO 19901 is applicable to all aspects of the life cycle and includes requirements relating to the manufacture of mooring components, as well as considerations for in-service inspections. Most stationkeeping systems used with mobile offshore units, the class covered by b), are termed “mobile mooring systems”. Throughout this part of ISO 19901, the term “floating structure”, sometimes shortened to “structure”, is used as a generic term to indicate any member of the two classes, a) and b).

This part of ISO 19901 is applicable to the following types of stationkeeping systems, which are either covered directly in this part of ISO 19901 or through reference to other guidelines:

— spread moorings (catenary, taut-line and semi-taut-line moorings);

— single point moorings, anchored by spread mooring arrangements;

— dynamic positioning systems;

— thruster-assisted moorings.

Descriptions of the characteristics and of typical components of these systems are given in Annex A.

The requirements of this part of ISO 19901 mainly address spread mooring systems and single point mooring systems with mooring lines composed of steel chain and wire rope. This part of ISO 19901 also provides

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guidance on the application of the methodology to synthetic fibre rope mooring systems, and includes additional requirements related to the unique properties of synthetic fibre ropes.

This part of ISO 19901 is applicable to single anchor leg moorings (SALMs) and other single point mooring systems (e.g. tower soft yoke systems) only to the extent to which the requirements are relevant.

This part of ISO 19901 is not applicable to the vertical moorings of tension leg platforms (TLPs).

The methodology described in this part of ISO 19901 identifies a set of coherent analysis tools that, combined with an understanding of the site-specific metocean conditions, the characteristics of the floating structure under consideration, and other factors, can be used to determine the adequacy of the stationkeeping system to meet the functional requirements of this part of ISO 19901.

NOTE For moorings deployed in ice-prone environments, additional requirements are given in ISO 19906.

2 Normative references

The following referenced documents are indispensable for the application 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.

ISO 19900, *Petroleum and natural gas industries — General requirements for offshore structures*

ISO 19901-1, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 1: Metocean design and operating considerations*

ISO 19904-1, *Petroleum and natural gas industries — Floating offshore structures — Part 1: Monohulls, semi-submersibles and spars*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
action
external load applied to the structure (direct action) or an imposed deformation or acceleration (indirect action)

EXAMPLE An imposed deformation can be caused by fabrication tolerances, settlement, temperature change or moisture variation.

NOTE An earthquake typically generates imposed accelerations.

[ISO 19900:2002]

3.2
action effect
effect of actions on structural components

[ISO 19900:2002]

EXAMPLE Internal forces, moments, stresses, strains, rigid body motions or elastic deformations.

3.3
catenary mooring
mooring system where the restoring action is provided by the distributed weight of mooring lines

[ISO 19900:2002]

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3.4
characteristic value
value assigned to a basic variable, an action or a resistance from which the design value can be found by the application of a partial factor

NOTE 1 The value usually has a prescribed probability of not being violated which, in the case of an action, will normally relate to a reference period.

NOTE 2 Adapted from ISO 19900:2002, definition 2.7.

3.5
design criteria
quantitative formulations that describe the conditions to be fulfilled for each limit state

[ISO 19900:2002]

3.6
design service life
assumed period for which a structure or a structural component is to be used for its intended purpose with anticipated maintenance, but without substantial repair being necessary

NOTE Adapted from ISO 19900:2002, definition 2.12.

3.7
design situation
set of physical conditions during a certain reference period for which the design will demonstrate that relevant limit states are not exceeded

NOTE Adapted from ISO 19900:2002, definition 2.13.

3.8
dynamic action
action that induces acceleration of a structure or a structural component of a magnitude sufficient to require specific consideration

3.9
dynamic positioning
DP
stationkeeping technique consisting primarily of a system of automatically controlled on-board thrusters, which generate appropriate thrust vectors to counter the mean and slowly varying induced actions

3.10
expected value
first-order statistical moment of the probability density function for the considered variable that, in the case of a time-dependent parameter, can be associated with a specific reference period

3.11
fit-for-purpose
fitness-for-purpose
meeting the intent of an International Standard although not meeting specific provisions of that International Standard in local areas, such that failure in these areas will not cause unacceptable risk to life-safety or the environment

[ISO 19900:2002]

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3.12
floating structure
structure where the full weight is supported by buoyancy

[ISO 19900:2002]

NOTE The full weight includes lightship weight, mooring system pre-tension, riser pre-tension, operating weight, etc.

3.13
limit state
state beyond which the structure no longer fulfils the relevant design criteria

[ISO 19900:2002]

3.14
maintenance
set of activities performed during the operating life of a structure to ensure it is fit-for-purpose

3.15
minimum breaking strength
MBS
RCS certified strength of a chain, wire rope, fibre rope or accessories

3.16
mobile mooring system
mooring system, generally retrievable, intended for deployment at a specific location for a short-term operation, such as those for mobile offshore units (MOUs)

3.17
mobile offshore drilling unit
MODU
structure capable of engaging in drilling and well intervention operations for exploration or exploitation of subsea petroleum resources

3.18
mobile offshore unit
MOU
structure intended to be frequently relocated to perform a particular function

[ISO 19900:2002]

EXAMPLE Pipelaying vessel or barge, offshore construction structure, accommodation structure (floatel), service structure, or mobile offshore drilling units.

3.19
mooring component
general class of component used in the mooring of floating structures

EXAMPLE Chain, steel wire rope, synthetic fibre rope, clump weight, buoy, winch/windlass, fairlead or anchor.

3.20
owner
representative of the company or companies which own a development, who can be the operator on behalf of co-licensees

3.21
permanent mooring system
mooring system normally used to moor floating structures deployed for long-term operations, such as those for a floating production system (FPS)

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3.22
proximity
closeness in distance

NOTE 1 Mooring systems are considered to be in proximity to a surface installation (or facility) if any part of the other installation lies within a contour described by the set of offsets coinciding with each line reaching 100 % MBS in the intact or redundancy check condition, whichever is larger.

NOTE 2 Mooring systems are considered to be in proximity to a sea floor installation (or facility) if any part of the other installation lies within a polygon formed by the anchor locations.

3.23
RCS
recognized classification society
member of the international association of classification societies (IACS), with recognized and relevant competence and experience in floating structures, and with established rules and procedures for classification/certification of installations used in petroleum-related activities

3.24
resistance
capacity of a structure, a component or a cross-section of a component to withstand action effects without exceeding a limit state

NOTE This definition is at variance with that specified in ISO 19900:2002.

3.25
return period
average period between occurrences of an event or of a particular value being exceeded

NOTE The offshore industry commonly uses a return period measured in years for environmental events. The return period is equal to the reciprocal of the annual probability of exceedance of the event.

[ISO 19901-1:2005]

3.26
riser
piping connecting the process facilities or drilling equipment on the floating structure with the subsea facilities or pipelines, or reservoir

NOTE 1 Possible functions include drilling and well intervention, production, injection, subsea systems control and export of produced fluids.

NOTE 2 Adapted from ISO 19900:2002, definition 2.29.

3.27
semi-submersible
floating structure normally consisting of a deck structure with a number of widely spaced, large cross-section, supporting columns connected to submerged pontoons

NOTE Pontoon/column geometry is usually chosen to minimize global motions in a broad range of wave frequencies.

3.28
serviceability
ability of a structure or structural component to perform adequately for normal functional use

3.29
significant value
statistical measure of a zero-mean random variable equal to twice the standard deviation of the variable

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3.30
single point mooring
mooring system that allows the floating structure to which it is connected to vary its heading (weathervane)

EXAMPLE One example of a single point mooring is a turret mooring system where a number of mooring lines are attached to a turret, which includes bearings to allow the structure to rotate.

3.31
ship-shaped structure
monohull floating structure having a geometry similar to that of ocean-going ships

3.32
spar platform
deep-draught, small water-plane area floating structure

3.33
spread mooring
mooring system consisting of multiple mooring lines terminated at different locations on a floating structure, and extending outwards, providing an almost constant structure heading

3.34
stationkeeping system
system capable of limiting the excursions of a floating structure within prescribed limits

3.35
structural component
physically distinguishable part of a structure

[ISO 19900:2002]

3.36
structure
organized combination of connected components designed to withstand actions and provide adequate rigidity

[ISO 19900:2002]

3.37
taut-line mooring
mooring system where the restoring action is provided by elastic deformation of mooring lines

[ISO 19900:2002]

3.38
thruster-assisted mooring
stationkeeping system consisting of mooring lines and thrusters

3.39
verification
examination made to confirm that an activity, product, or service is in accordance with specified requirements

3.40
weathervaning
process by which a floating structure passively varies its heading in response to time-varying environmental actions

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4 Symbols and abbreviated terms

4.1 Symbols

C coefficient (non-dimensional unless otherwise specified)

D annual fatigue damage, in years^{-1}

d diameter of the mooring line or component, in metres (m)

F direct action, in newtons (N), or a direct action per unit length, in newtons per metre, (N/m)

f frequency, in hertz (Hz)

K fatigue constant (non-dimensional unless otherwise specified)

k axial stiffness, in newtons per metre (N/m)

L design service life, in years

l length, in metres (m)

M mass, in kilograms (kg)

m inverse slope of T-N or S-N fatigue curves

N total number of (permissible) cycles

n number of cycles per annum, in year^{-1}

P probability of occurrence

S offset or motion, in metres (m)

S_R stress range, in megapascals (MPa)

s standard deviation

T tension force, in newtons (N); or non-dimensional tension ratio

t time, period or duration, in seconds (s)

v velocity, in metres per second (m/s)

W submerged weight, in newtons (N), or weight per unit length, in newtons per metre (N/m)

Γ gamma function

γ design safety factor

δ bandwidth parameter for the wave frequency

ε annual creep elongation, percent per year

σ ratio of the standard deviation of the tension variations around the mean tension to a reference breaking strength

ρ density, in kilograms per cubic metre (kg/m^3)

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4.2 Abbreviated terms

ALS accidental limit state

CALM catenary anchor leg mooring

DP dynamic positioning

FEA finite element analysis

FLS fatigue limit state

FMEA failure modes and effects analysis

FPS floating production system

FPSO floating production, storage and offloading structure

FSO floating storage and offloading structure

HMPE high modulus polyethylene

IACS International Association of Classification Societies

IMCA International Marine Contractors Association

IMO International Maritime Organization

LTM long-term mooring

MBS minimum breaking strength

MDS mooring design states

MODU mobile offshore drilling unit

MOU mobile offshore unit

ORQ oil rig quality

RAO response amplitude operator

RCS recognized classification society

ROV remotely operated vehicle

SALM single anchor leg mooring

SAW submerged arc welding

SIM structural integrity management

SLS serviceability limit state

TAM thruster-assisted mooring

TLP tension leg platform

ULS ultimate limit state

VIM vortex-induced motion

VIV vortex-induced vibration

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5 Overall considerations

5.1 Functional requirements

The function of a stationkeeping system is to restrict the horizontal excursion of a floating structure within prescribed limits, as well as to provide means of active or passive directional control when the structure's orientation is important for safety or operational considerations.

The limiting criteria for excursions and orientation are generally established either by the owner of the floating structure or by direct derivation from design requirements including those related to

— safety of personnel,

— protection of the environment,

— stability and serviceability of the floating structure,

— serviceability of the topsides equipment,

— integrity and serviceability of drilling, production, export or other types of risers,

— access to and clearances with respect to nearby subsea or surface installations, and

— any other special positioning requirement.

Compliance of the stationkeeping system design with the requirements outlined above shall be established using the analysis methodologies given in Clauses 8 and 9, and the design criteria specified in Clause 10. The effects of external actions on the floating structure such as line tensions, structure offsets and anchor forces shall be evaluated for all relevant design situations, and shall be compared with the system and component resistances to ensure the existence of reserve strengths against mooring line breakage, offset exceedance, anchor slippage or other undesirable occurrences.

5.2 Safety requirements

Safety of life, environment and property shall be the main principles to be respected at all times through

— competent design or assessment, which ensures the ability of the floating structure and its stationkeeping system to withstand environmental and other external actions likely to occur during the design service lives of the structure and stationkeeping system, or duration of site-specific deployment of an MOU,

— definition of safe operating procedures so that risks of injuries to personnel are identified and minimized,

— identification and assessment of possible accidental events, as summarized in ISO 19900, and minimization of their consequences,

— performance of a risk assessment to ensure that possible malfunctions do not pose a danger to life or structure integrity, and

— compliance with all relevant regulations, see ISO 19904-1.

The implications of the above items shall be incorporated in the stationkeeping system design or assessment, and in the development of the operational philosophy.

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5.3 Planning requirements

Planning shall be carried out before actual design or assessment is started in order to ensure that the stationkeeping system is able to perform its intended function according to 5.1. The initial planning shall include the determination of all conditions and criteria, in accordance with the general requirements and conditions specified in ISO 19900.

5.4 Inspection and maintenance requirements

The integrity of a stationkeeping system and its serviceability throughout the design service life are not only strongly dependent on a competent design, but also on the quality control exercised in manufacture, the supervision on-site, handling during transport and installation, and the manner in which the system is used and maintained.

At the planning stage, a philosophy for inspection and maintenance shall be developed and documented, to ensure full consistency with the design of the stationkeeping system and its components. A critical assessment shall be made of the ability to actually achieve the intended objectives through inspection and maintenance efforts. Relevant requirements related to inspection and maintenance requirements are given in Clause 12.

5.5 Analytical tools

Most of the analytical procedures and calculations described, specified and referenced in this part of ISO 19901 are commonly performed with the assistance of computer-aided engineering tools. Many of these consist of commercially available, widely used software suites which, when employed by experienced and well-trained users, may be considered *de facto* industry standards. For these software systems, the original author is expected to have performed adequate validation and verification, and to maintain evidence thereof.

In other cases, particularly in technological areas undergoing rapid evolution, innovative analytical approaches and techniques are often embedded in original, proprietary software solutions. In such cases, the developer is expected to validate the adequacy of the results by, for instance, comparison with test data or field measurements.

In any case, the designer shall document that the tools and modelling protocols used in the design and analysis activities have been shown to provide results considered acceptable in terms of consistency and accuracy when compared to test data, field measurements, or to the results of other similar tools.

6 Design requirements

6.1 Exposure levels

6.1.1 General

Like all offshore structures, floating structures vary in size, complexity, mission, performance requirements, manning levels, criticality to the asset development strategy, possible hazards, etc. In order to define appropriate design situations and design criteria for a particular structure, the concept of exposure levels was introduced.

According to this philosophy, an offshore structure at a particular location is characterized by a specific exposure level. Associated with each exposure level are appropriate design situations and design criteria for the structure's intended service.

Exposure levels are determined considering in combination life safety and consequences of failure for a given structure. Life safety is a direct function of the structure's expected manning levels during the environmental design situation. Consequences of failure are mainly related to the potential risk to life of personnel brought in to respond to any incident, the potential risk of environmental damage and the potential risk of economic losses.

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These concepts and definitions apply to the design of the class of floating structures covered under a) but not to those of b) (mobile offshore units) as given in the Scope of this part of ISO 19901.

The definition of the exposure level for floating structures is given in ISO 19904-1.

6.1.2 Exposure levels for stationkeeping systems

The exposure level assigned to a permanent stationkeeping system shall be no less onerous than the exposure level of the floating structure to which it is connected.

6.2 Limit states

6.2.1 General

The general principles on which design requirements for offshore structures are based are documented in ISO 19900. These state that design verification of a system and its components shall be performed with reference to a specified set of limit states beyond which the structure or the system no longer satisfies the requirements of Clause 5.

For each limit state, appropriate design situations shall be defined, calculation models shall be established, design criteria shall be defined, and adequate procedures shall be followed to verify compliance with design requirements.

6.2.2 Limit states for stationkeeping systems

ISO 19900 identifies four categories of limit states:

— ultimate limit states (ULS);

— serviceability limit states (SLS);

— fatigue limit states (FLS);

— accidental limit states (ALS).

6.3 Defining design situations

The definition of specific design situations for the stationkeeping system is the responsibility of the owner in accordance with the requirements of a regulatory authority where one exists. Aspects to be considered in determining design situations include

— service requirements for the stationkeeping system,

— design service life,

— hazards (e.g. accidental events) to which the stationkeeping system and the connected floating structure can be exposed during its design service life,

— potential consequences of partial or complete stationkeeping system failure, and

— nature and severity of environmental conditions to be expected during the design service life.

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6.4 Design situations

6.4.1 General

Provisions related to the consideration of environmental conditions and their application are given in ISO 19900, and these shall be complied with in conjunction with the further requirements of ISO 19901-1 and those of this part of ISO 19901.

Design situations include all the service and operational requirements resulting from the intended use of the floating structure and the environmental conditions that could affect the stationkeeping system according to ISO 19900.

In particular, an environmental design situation consists of a set of actions induced by waves, wind, current and ice (if any) on the floating structure, on the risers and on the mooring system, as applicable, and is characterized by a given return period for one or more environmental variables or for a contour of environmental variables.

In the absence of site-specific information on environmental conditions, ISO 19901-1 gives an approximate indication of the extreme conditions for certain geographic areas. These values are meant to be indicative only (e.g. for conceptual design studies). The owner shall review the validity of these values and, if necessary, use site-specific data for the final design instead of those provided therein.

Criteria to be met by the design can be directly related to the specific formulation of the design situations. In this case, design situations, calculation process and design criteria are interrelated and should not be separated from one another.

For permanent moorings, the design situations detailed below apply to mooring systems for floating structures with an L1 exposure level — see ISO 19904-1 for the definition of exposure levels.

6.4.2 Design situations for ULS

6.4.2.1 General

The parameters specifying the environmental design situation should be developed from the environmental information as described in 6.4.2.2 for permanent moorings and 6.4.2.3 for mobile moorings.

6.4.2.2 Permanent moorings

6.4.2.2.1 General

For permanent moorings, the return periods of the parameters that characterize environmental design situations should be several times the design service life of the stationkeeping system.

Parameters characterizing ULS environmental design situations in this part of ISO 19901 shall be based on a return period of 100 years, except as specified below.

6.4.2.2.2 Permanent moorings with a short design service life

When the design service life of the mooring system is substantially lower than 20 years, parameters characterizing design situations with return periods shorter than 100 years may be adopted. In such cases, the return period shall be determined through a risk assessment, taking into account the possible consequences of mooring system failure.

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6.4.2.2.3 Permanent moorings designed for disconnection

Mooring systems can be designed to disconnect from the floating structure in advance of certain adverse environmental events, e.g. iceberg impact or hurricanes. The actions on the floating structure due to such adverse events may be ignored at the ULS, provided that either

a) an appropriate ALS is satisfied, consisting of the adverse environmental event combined with a failure to safely disconnect, or

b) the joint probability of occurrence of the adverse environmental event combined with the failure to disconnect is less than 10^{-4} per annum.

Furthermore, the mooring system design shall also be verified for a ULS design situation consisting of the actions of waves, wind, current and ice (if any) on the mooring system alone (i.e. without the floating structure).

6.4.2.2.4 Permanent moorings in proximity to other installations

When permanent moorings are in proximity to other installations, consideration should be given to increasing the return period of the design situation parameters for the moorings, in order to account for the possible consequences of contact with surface, mid-depth or sea floor infrastructures or installations.

6.4.2.2.5 Permanent moorings redundancy check condition

Permanent moorings shall be designed with sufficient redundancy so as to withstand the appropriate design situations (see 6.4.2.2.1 to 6.4.2.2.4) even after the loss of any one mooring line or any one or more thrusters as appropriately assessed by the failure modes and effects analysis (FMEA). This can be the consequence of accidental breakage, planned maintenance or local failure.

6.4.2.3 Mobile moorings

6.4.2.3.1 Mobile moorings for structures not in proximity to other installations

Environmental design situations for mobile moorings not in proximity to other installations shall be characterized by parameters with a return period of at least 5 years.

A risk analysis examining various mooring failure scenarios shall be conducted to evaluate the consequence of a mooring failure to demonstrate that the risk posed by loss of station is acceptable.

In tropical cyclone areas, the wind speed should be ≥ 30 m/s (1 min average at 10 m height).

6.4.2.3.2 Mobile moorings for structures in proximity to other installations

When mobile moorings are in proximity to other installations, the environmental design situation shall be characterized by parameters with return periods of at least 10 years, to account for the possible consequences of contact with surface, mid-depth or sea floor infrastructures or installations.

6.4.2.3.3 Mobile moorings redundancy check condition

Mobile moorings shall be designed with sufficient redundancy to be able to withstand the appropriate design situations (see 6.4.2.3.1 and 6.4.2.3.2) even after the loss of any one mooring line or any one or more thrusters as appropriately assessed by the FMEA. This can be the consequence of accidental breakage, planned maintenance or local failure.

6.4.3 Design situations for SLS

Design situations for SLS shall be defined by the owner either directly or with reference to a specific percentage of time on station when the structure is required to fulfil its intended mission.

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6.4.4 Design situations for FLS

Design situations for FLS shall consist of a set of environmental states described by

— wave period, height and direction,

— wind speed and direction,

— current speed, profile and direction (see 8.3.5.5 for VIM-related issues), and

— the frequency of occurrence of each environmental state,

adequately representing the long-term statistics of the local environment, see Clause 9.

6.4.5 Design situations for ALS

No ALS events are specified for stationkeeping systems in this part of ISO 19901, except those of 6.4.2.2.3, to be applied as appropriate. However, consideration should be given to performing a site-specific assessment to establish the nature and probability of possible ALS design situations, e.g. iceberg impact. Accidental events with return periods in excess of 10 000 years may be neglected.

7 Actions

7.1 General

This clause addresses the main actions to be considered in the design of stationkeeping systems. As floating structure motions and offsets are generally the main contributors to stationkeeping system design, it also includes actions applied only to the floating structure, which result in indirect actions applied to the stationkeeping system.

7.2 Site-specific data requirements

7.2.1 Data collection and analysis

The interaction of environmental phenomena, such as wind, waves, current and tide, is site-specific. The joint probability distribution describing these actions should be considered in the development of the analytical and statistical models intended to predict actions and their effects.

When collecting data where joint probabilities are to be considered, care shall be exercised to preserve the appropriate information. Of particular importance are the wind/wave, wave height/wave period, and wave/current relationships and their absolute and relative directionality characteristics.

There are areas governed by special metocean phenomena that are not well represented by parameters with typical return period statistics. For example, some areas of generally mild climate can be subject to “sudden storms” such as squalls, and other areas can be subject to occasional very high currents. In these cases, the special occurrences shall be considered in determining the relevant environmental conditions.

The environmental action characteristics defining design situations for mobile moorings shall be determined from annual statistics. However, if the operating season is well defined, and seasonal environmental data are sufficient to provide meaningful statistics, these characteristics may be determined from seasonal statistics.

For fatigue analyses, wave, wind and current data shall be collected sufficient to satisfy 6.4.4.

Further information on data description and the data gathering procedures can be found in ISO 19901-1.

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7.2.2 Water depth

The design water depth for the mooring system at each anchor location shall account for sea level variations due to tides and storm surges.

7.2.3 Soil and sea floor conditions

Sea floor soil conditions shall be investigated for the intended site to provide data for the anchoring system design. The sea floor slope shall be properly accounted for in the mooring analysis, when relevant. For permanent moorings a bottom survey shall be performed.

7.2.4 Wave statistics

The wave height versus wave period and wave direction relationships for the design situations shall be accurately determined from oceanographic data for the area of operation.

7.2.5 Wind statistics

Wind speed and direction data shall be accurately determined from the oceanographic data for the site under consideration.

7.2.6 Current profile

Current speed and direction data shall be collected from the oceanographic data for the area of operation. Appropriate consideration of current profiles on mooring lines/risers is often necessary for more detailed accurate analytical representations.

7.2.7 Atmospheric icing

Where applicable, an assessment shall be made of atmospheric icing, including sea spray icing. Increased wind area due to superstructure icing shall be considered in the calculations of wind actions on a floating structure.

7.2.8 Marine growth

The type and accumulation rate of marine growth at the design site can affect mass, weight, hydrodynamic diameters, and drag coefficients of floating structure members and mooring lines. This shall be taken into consideration for permanent mooring systems not subject to any regular marine growth removal.

7.3 Environmental actions on mooring lines

7.3.1 General

In this subclause, methods for evaluating direct environmental actions on mooring lines are summarized. Mooring lines are typically modelled as slender cylindrical members. Direct wave actions on mooring lines may generally be neglected.

7.3.2 Current-induced actions

The effect of current actions on mooring lines on the overall mooring design shall be evaluated. Current actions are likely to be particularly important for deepwater locations with high currents. Actions on mooring lines due to currents can be calculated from Equation (1):

$$F = 1/2 \rho_{\mathrm{w}} C_{\mathrm{d}} \cdot d \cdot v^2 \qquad (1)$$

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where

F is the force per unit length normal to the local mooring line, in newtons per metre (N/m);

ρ_w is the density of the seawater, in kilograms per cubic metre (kg/m^3);

C_d is the drag coefficient, see relevant RCS rules;

d is the nominal diameter of the mooring line, in metres (m);

v is the component of current velocity normal to the local mooring line, in metres per second (m/s).

Where there are high currents, drag coefficients should be adjusted for the presence of vortex-induced vibrations.

7.3.3 Ice-induced actions

In ice-prone areas, ice-induced actions on the mooring system shall be in accordance with ISO 19906.

7.3.4 Vortex-induced vibrations of mooring lines

For smooth cylindrical mooring lines the possibility of vortex-induced vibrations (VIV), in particular the effect on drag coefficient, should be considered.

7.4 Indirect actions

7.4.1 General

Floating structure offset and motions are the main indirect actions on a stationkeeping system. The details of the calculation of environmental actions on the floating structure are presented in ISO 19904-1.

7.4.2 Frequency ranges

For the purpose of assessing their effects, and sometimes considering their relative influence, environmental actions on floating structures can be categorized as follows according to their frequency range.

— Steady actions, such as wind, current and wave drift, which are constant in magnitude and direction for the duration of interest.

— Low-frequency cyclic actions (often referred to as slow drift), with characteristic periods between 1 min and 10 min, which typically induce dynamic excitation of floating structures at their natural periods in surge, sway and yaw. In spar platforms these actions can also induce dynamic excitation at the pitch and roll natural periods;

— Wave-frequency cyclic actions with characteristic periods ranging from 3 s to 30 s.

7.4.3 Wave-induced actions

Wave-induced actions (steady, low-frequency and wave-frequency) shall be determined by relevant analytical or empirical methods or model testing, with appropriate consideration of water depth effects. Relevant analytical/empirical methods include diffraction and radiation theory, and slender member hydrodynamics.

As the wave period can significantly affect slow drift motions, a range of wave periods should be investigated in accordance with A.7.2.4.

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Interaction between current and waves shall be examined. This includes the change in intrinsic wave frequencies to apparent wave frequencies (see ISO 19901-1) as well as changes in the magnitudes of wave-induced actions.

7.4.4 Wind-induced actions

Drag coefficients shall be determined by means of wind tunnel tests and/or empirical analysis tools, see ISO 19904-1. The constant wind action from a particular direction should incorporate all three horizontal plane components (F_x, F_y, M_z) using force coefficients derived from model tests or calculation. For spars, wind pitch and roll moments are also important as the mean pitch and roll angle will also have an impact on the surge, sway and yaw wind action coefficients.

Two analytical approaches are generally used to represent steady and low-frequency wind actions (see ISO 19904-1):

a) the wind is treated as constant in direction and speed, which is taken as the 1 min average;

b) the wind is modelled by a steady component, based on the 1 h average velocity, plus a time-varying component calculated from a suitable empirical wind gust spectrum, see ISO 19901-1.

The design wind speed should refer to an elevation of 10 m above still water level.

For ULS design of permanent moorings, approach b) shall be taken; approach a) may also be used provided it can be shown to be more conservative. However, for FLS, b) shall be used because the effect of time-varying wind actions on the floating structure can contribute to the magnitude of the low-frequency tension cycles.

For mobile moorings, either a) or b) may be used.

For sites affected by tropical squalls, the concept of a wind spectrum is not applicable. The analysis of corresponding wind-induced actions and effects should be performed using an appropriate specification of a wind speed time history.

7.4.5 Current-induced actions

Current-induced actions (steady and low-frequency) on large body floating structures shall be determined by means of model tests and/or empirical analysis tools. Current-induced actions on slender members, including risers, may be determined using Equation (1).

7.4.6 Directional distribution

The floating structure offsets and motions to be used in the stationkeeping system design shall be evaluated for the most unfavourable combinations of wind directions, wave directions and current directions, consistent with the site-specific metocean characteristics. The ability of the floating structure to change heading in response to changing environmental conditions may be taken into account.

7.4.7 Vortex-induced motions of floating structures

Floating structures consisting of large diameter cylindrical components such as spars, semi-submersibles, and TLPs can experience low-frequency motions due to vortex shedding in the presence of currents. These vortex-induced motions (VIM) are most prominent for spars where most of the industry experience has been acquired. Nevertheless, multi-column floating structures such as semi-submersibles and TLPs can also experience VIM and this effect should be taken into account in their design.

VIM has three primary effects on the mooring design:

a) the average in-line drag coefficient is higher than the value it would have in the absence of VIM;

b) the low frequency VIM motions can be significant in terms of the total floating structure response;

c) the VIM motions cause additional low frequency oscillating mooring line tensions.

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These effects should be taken into account for strength and fatigue design of the mooring system. The occurrence of the Loop Current and associated eddies in the Gulf of Mexico make consideration of VIM particularly important for this geographic area. For example, unlike other extreme events, e.g. winter storms and hurricanes, the Loop Current and associated eddies can affect a particular site for an extended period of time and can make a significant contribution to the fatigue damage of mooring components.

NOTE Waves transverse to a current can amplify VIM motions due to current only, dependent on wave frequency, so wave effects should be considered in a VIM analysis, if applicable.

8 Mooring analysis

8.1 Basic considerations

8.1.1 Introduction

Mooring analysis shall be performed to predict extreme values of action effects (maximum or minimum, as applicable) such as floating structure offsets, line tensions and anchor forces under environmental and other actions (riser actions, tandem mooring actions, etc.). The extreme action effect values shall be checked against the design criteria given in Clause 10.

Mooring line tensions are often manually adjusted for operational reasons and/or in advance of foreseeable environmental events. For the analysis of ULS design situations, the modelling of the stationkeeping system and floating structure configuration shall reflect such adjustments. However, the modelling of active adjustment of line tensions during the analysis of design situations shall not be taken into account.

The value of the mooring line diameter used in the mooring line analysis shall be the nominal value (i.e. with no deduction for corrosion or wear), unless noted otherwise below.

8.1.2 Mooring analysis conditions

8.1.2.1 General

Mooring analysis shall be carried out in accordance with 8.8 for the intact, redundancy check and transient conditions as defined below. Descriptions of analysis conditions for thruster-assisted moorings are given in 8.9.2.

Installation tolerances on anchor placement and line length should be taken into account in the mooring system design.

8.1.2.2 Intact condition

This is the condition in which all mooring lines are intact and all thrusters, if any, are working.

8.1.2.3 Redundancy check condition

This is the condition in which the structure has a new mean position after a single mooring line breakage or a failure of one or more thrusters as appropriately assessed by the FMEA.

A risk assessment of the stationkeeping system shall be performed if the structure is in the redundancy check condition.

8.1.2.4 Transient condition

This is the condition in which the structure undergoes transient motions between the intact and redundancy check conditions, including the possibility of overshooting, as a result of a single mooring line breakage or a failure of one or more thrusters as appropriately assessed by the FMEA.

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8.1.2.5 Recommended analysis methods and conditions

The analysis methods (see 8.3.5) recommended to be used, depending on the conditions to be analysed and the limit states to be satisfied, are given in Table 1.

Table 1 — Recommended analysis methods and conditions

Type of mooring	Limit state	Conditions to be analysed	Analysis method
Permanent mooring	ULS	Intact/Redundancy check	Dynamic
		Transient [a]	Quasi-static or Dynamic
	FLS	Intact	Dynamic
	SLS	No guidance given	No guidance given
Mobile mooring	ULS	Intact/Redundancy check	Quasi-static or Dynamic
		Transient [a b]	Quasi-static or Dynamic
	FLS	Not required	Not applicable
	SLS	No guidance given	No guidance given

[a] Applicable only if another installation is in proximity to the mooring.

[b] Applicable for MODUs drilling in deepwater where excessive transient motions can cause stroke-out of the riser slip joint.

8.2 Floating structure offset

8.2.1 General

The following definitions of floating structure offset apply to any chosen reference point on the structure.

8.2.2 Mean offset

The mean offset is defined by the structure's rigid body displacement due to the combination of the steady components of wind, wave, current and other external actions. While, in general, only the three components in the horizontal plane (in the surge, sway and yaw directions) are taken into account, the other three components (in the heave, roll and pitch directions) can also be significant, in particular for small water-plane area structures.

8.2.3 Extreme values of offset

When the frequency-domain approach, 8.3.1.2, is used to compute the structure response, the extreme values of the offset are defined as the mean offset plus or minus the maximum estimated value of the time-varying excursion due to combined wave-frequency and low-frequency structure motions. Extreme values of the offset shall be also calculated relative to each anchor location for the purpose of tension calculation.

The extreme values of the offset, S_{max} and S_{min} can be determined by Equations (2) and (3).

$$S_{max} = S_{mean} + \mathrm{MAX}\,(S_{dyn1}, S_{dyn2}) \quad (2)$$

$$S_{min} = S_{mean} - \mathrm{MAX}\,(S_{dyn1}, S_{dyn2}) \quad (3)$$

$$S_{dyn1} = S_{lfmax} + S_{wfsig} \quad (4)$$

$$S_{dyn2} = S_{wfmax} + S_{lfsig} \quad (5)$$

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where

MAX is the larger of the absolute values of the terms in parentheses;

S_{max} is the maximum structure offset, in metres (m);

S_{min} is the minimum structure offset, in metres (m);

S_{mean} is the mean structure offset, in metres (m);

S_{lfmax} is the most probable maximum value of low-frequency motion, in metres (m);

S_{lfsig} is the significant value of low-frequency motion, in metres (m);

S_{wfmax} is the most probable maximum value of wave-frequency motion, in metres (m);

S_{wfsig} is the significant value of wave-frequency motion, in metres (m).

Definitions of most probable maximum and significant values are given in 8.3.2.

The combined offset for different degrees-of-freedom (e.g. surge and sway) should be defined as the vector sum of the individual components of the offset.

Alternatives to this approach are the time-domain approach, 8.3.1.3, and the combined time-and-frequency-domain approach, 8.3.1.4, which involve statistical processing of simulated time histories to yield extreme values of the offsets.

The above subclause applies to the intact and redundancy check conditions. For the transient condition, extreme values of the offset are defined in 8.10.2.

8.3 Floating structure response

8.3.1 Analysis methods

8.3.1.1 General

The three methods generally used to compute floating structure response are

— the frequency-domain approach,

— the time-domain approach,

— the combined time- and frequency-domain approach.

These methods involve different degrees of approximation and are affected by different limitations, and therefore do not necessarily yield consistent results. If verification of the approach selected for the mooring design is required, model test data or an alternative approach should be used.

Currently, as there is no established analytical method for determining the motion response of floating structures undergoing VIM, the industry relies mainly on model testing. However, limited full-scale data are available to confirm the scalability of model testing. If current loadings and VIM are determined to be a design driver, it is usual practice to perform well planned model tests to determine motion amplitudes and drag coefficients for use in mooring design.

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8.3.1.2 Frequency-domain approach

In this approach, the general equations of motion describing the response of the structure are decoupled and analysed separately for mean, low- and wave-frequency responses. Mean responses are calculated from static equilibrium between the steady environmental actions and the mooring system's restoring force. Wave-frequency and low-frequency structure motions are calculated from the frequency-domain approach which yields motion response statistics. Extreme values, such as significant and most probable maximum responses, are then evaluated based on peak probability density distributions, see 8.3.2. Finally, the most probable maximum values and significant values of wave-frequency and low-frequency responses are combined with the mean response, Equations (2) and (3), to yield the combined most probable maximum response for a specified storm duration.

To perform a frequency-domain analysis of a weathervaning structure, the structure's heading shall be fixed. The fixed design headings at which the mooring system responses are calculated shall be determined, taking into consideration the mean equilibrium heading and low-frequency yaw motions. Normally more than one fixed heading shall be considered to ensure the largest maximum has been identified, see 8.8.2.

8.3.1.3 Time-domain approach

In this approach, the general equations of motion describing the combined mean, low-frequency and wave-frequency responses of the floating structure are solved in the time domain. The forcing functions include the mean, low-frequency and wave-frequency actions due to wave, wind, current and thrusters, if any. The equations describing the floating structure, mooring lines, risers and thruster behaviour and their interactions are all included in the time-domain simulation. Time histories of all main response parameters (structure displacements, mooring line tensions, anchor forces, etc.) are obtained from the simulation, and the resulting time histories are then processed statistically to yield extreme values. The time-domain simulation should be long enough to yield stable statistical values.

8.3.1.4 Combined time-domain and frequency-domain approach

To reduce the complexity and computational effort associated with the fully coupled time-domain simulation, a combined time- and frequency-domain approach is often employed. Time- and frequency-domain solutions for mean responses, wave and low-frequency responses can be combined in different ways. In a typical approach, the mean and low-frequency responses (structure displacements, mooring line tensions, anchor forces, etc.) are simulated in the time domain while the wave-frequency responses are solved separately in the frequency domain. The frequency-domain solution for wave-frequency response is processed to yield either statistical extreme values or time histories, which are then superimposed on the mean and low-frequency responses.

8.3.2 Extreme value statistics

For time-domain analysis, relevant extreme values can be determined in accordance with A.8.3.1.3.

In frequency-domain analysis, for phenomena that can be represented by a narrow-banded Gaussian process, extreme value statistics for the time-varying component of the phenomenon can be calculated from the standard deviation of the relevant response spectrum as follows (Rayleigh distribution):

$$V_{\text{sig}} = \pm 2s \tag{6}$$

$$E_{\text{max}} = +s\sqrt{2\log_e(t/t_z)} \tag{7}$$

$$E_{\text{min}} = -s\sqrt{2\log_e(t/t_z)} \tag{8}$$

where

V_{sig} is the significant value;

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E_{max} is the most probable maximum value;

E_{min} is the most probable minimum value;

s is the standard deviation;

t is the duration of the design situation, in units of time; a minimum of 3 h should be specified for the duration of the design situation;

t_z is the average zero up-crossing period of the motions, in units of time, where, for low-frequency motions, t_z can be taken as the natural period for the appropriate degree-of-freedom of the combined structure/riser/mooring system t_n, which can be estimated by

$$t_n = 2\pi\sqrt{M/k} \tag{9}$$

M is the system mass including added mass, in kilograms, (kg);

k is the system stiffness for the appropriate degree-of-freedom at the structure's mean position, in newtons per metre (N/m).

The most-probable maximum tension, to be compared with the line tension limits in 10.2, can be obtained from Equation (7) by adding the value of the mean tension.

NOTE These formulations can under-predict the most probable maximum value in cases of non-linear wide band response.

8.3.3 Low-frequency damping

Special attention should be given to low-frequency damping. Low-frequency motion of a moored structure is narrow-banded in frequency since it is dominated by the resonant response at the natural frequency of the moored structure. The motion amplitude is highly dependent on the stiffness of the mooring system and the damping. There is a substantial degree of uncertainty in the estimation of low-frequency damping of which there are four main sources:

— viscous damping of the structure;

— wave drift damping of the structure;

— mooring system damping;

— riser system damping.

8.3.4 Riser considerations

The riser system (if any) interacts with the floating structure and the mooring in several aspects. Wave and current actions on the risers increase the environmental actions to be resisted by the mooring, while the riser system stiffness provides assistance to the mooring. Furthermore, damping from the riser system decreases the low-frequency motions and in turn reduces the mooring tensions. The net result of these effects depends on a number of factors such as type and number of risers, and water depth. Mooring design should take into consideration the riser actions, stiffness and damping. The risers effects may be ignored if doing so results in a more conservative mooring design.

If a riser system is designed for different numbers of risers during its design service life (e.g. associated with later tie-in) all the different configurations shall be investigated.

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8.3.5 Vortex-induced motion considerations

8.3.5.1 General

Unlike other resonant responses, the amplitude of VIM is bounded. Transverse motion behaviour is usually characterized by the non-dimensional ratio of the motion amplitude, a, to the body's diameter, d, (a/d). The largest single amplitude transverse motion observed on bluff bodies is on the order of a/d = 1. Helical strakes are commonly used on spars (and risers) to reduce the motion amplitude. Strakes can be very effective in eliminating VIM; however their effectiveness on spars depends on various factors, such as the exact layout and size of the strakes, appurtenances, and current profiles.

Special issues for VIM design and analysis include but are not limited to the following.

a) There is no established analytical tool for the prediction of VIM. Currently VIM design criteria are typically obtained from model testing. Model testing practices should be validated with field measurement data, which are quite limited.

b) VIM is affected by the natural periods of the combined floating structure and stationkeeping system, current velocity, direction, profile, hull geometry and appurtenances.

c) The duration of current resulting in VIM can be much longer than peak storm duration.

d) Model tests can only model certain parameters while approximating others, hence care should be exercised in the interpretation and use of model test data.

e) Where VIM results in large tension cycles at high mean load, fatigue life can be short for mooring components with low fatigue resistance such as chain.

f) The calibration of the factors of safety for mooring design does not include the VIM condition and the uncertainties associated with VIM. Consequently, sensitivity checks as described in A.8.3.5.1 are recommended.

Because of the above issues, it is important to address VIM conservatively in the mooring design stage. This can be achieved through the following measures:

— establishing design criteria that recognize the uncertainties in VIM behaviour, for example checking sensitivity cases in addition to the base case and checking field measurement data as well as model test data;

— conducting fatigue analysis for the 100-year VIM response condition in addition to long term fatigue analysis;

— selecting mooring hardware and system design characteristics that can better tolerate or mitigate VIM.

8.3.5.2 Design criteria for VIM strength analysis

The first step in strength design is to establish suitable VIM design criteria. VIM-related design parameters for mooring strength design include:

— in-line and transverse VIM response amplitude (a/d) as a function of reduced velocity (V_r);

— drag coefficient as a function of VIM response amplitude;

— definition of ranges for V_r;

— VIM response trajectory or envelope.

These criteria are generally based on a combination of project specific model test data and previous VIM design experience. Depending on the approach taken, there can be varying levels of uncertainty in the VIM

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criteria specified for a particular application. Criteria should be developed for a base case (the best estimate) and for some sensitivity cases. Tension safety factors for intact and damaged conditions should be met for the base case. Sensitivity cases should be used to check the robustness of the mooring system design, with the intent of confirming that the risk of mooring failure is at an acceptable level even in the event that estimates of certain influential parameters such as mooring stiffness, current velocity, drag coefficient, lock-in definition, or VIM amplitude, are inaccurate. One of the important roles of the sensitivity check is to determine if, with some limited changes in critical parameters, the system would enter a VIM lock-in regime that would not be apparent for the base-case design criteria alone.

8.3.5.3 VIM strength analysis method

Most mooring analysis software is not generally designed to handle VIM analysis, and therefore the simplified analysis procedure described in the informative annex is typically used.

8.3.5.4 Basic considerations for VIM fatigue analysis

VIM-induced mooring tensions are of a cyclic nature, and contribute to the mooring system fatigue damage. The following factors should be considered when assessing fatigue due to VIM:

a) For the calculation of the number of tension cycles, use should be made of the VIM period in the offset position, corresponding to the specific current bin under consideration. This period can vary with current direction and magnitude and is generally different from the still water natural period.

b) In addition to a long-term fatigue damage evaluation, a fatigue analysis for the 100-year VIM fatigue event (or other single worst-case event as noted in 8.3.5.5) is also recommended.

c) Mooring systems experiencing a high mean tension and large tension variation can stress the chain beyond the elastic region, where fatigue test data are not available. To ensure sufficient fatigue life, mooring systems should be designed to avoid this situation.

d) Fatigue damage of chain at the fairlead requires special attention since additional bending stress is imposed on the chain in this region, and chain typically has the lowest fatigue life of all the components in the mooring system.

e) Sensitivity cases, similar to those used in the strength analysis, should be considered to account for uncertainty in the VIM predictions.

8.3.5.5 VIM fatigue analysis for long term and single extreme events

For long-term fatigue analysis under VIM conditions, current events can be represented by a number of discrete current bins, with each current bin consisting of a reference direction, a reference current velocity and profile, associated wave and wind conditions, and probability of occurrence. Fatigue damage for each current bin is evaluated, and the fatigue damage due to VIM is combined with the fatigue damage due to wind and waves to yield total fatigue damage.

However, studies indicate that considerable fatigue damage can be caused even by a single extreme VIM event. Consequently, in addition to the long-term fatigue damage evaluation, a fatigue analysis of the 100-year VIM event should be considered. Since VIM response is largely dependent on the reduced velocity, the current associated with the worst-case VIM design situation does not necessarily coincide with the 100-year return period loop or hurricane current. The VIM amplitudes that induce the highest fatigue damage can occur in the presence of currents with lower return periods. The current speed profile and direction used in the single event fatigue assessment should be the most onerous speed profile and direction identified in the strength analysis. However, instead of using a constant current speed profile for the whole extreme event, current variation based on field measurements for strong loop currents can be considered. The duration of this event can be different from that obtained from the long-term current distribution.

Fatigue analysis is typically performed for the intact condition only. However, a fatigue analysis of the damaged condition should be considered for the single extreme VIM event when progressive line failure due to fatigue is a concern.

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The factor of safety for fatigue design is given in 10.5. This factor should be applied to the long-term fatigue damage (due to both wind and waves and VIM) and to the single event fatigue damage under the intact condition.

8.3.5.6 VIM chain fatigue and wear

Fatigue damage of chain at the fairlead is typically higher than that away from the fairlead. For mooring systems where chain fatigue is critical, it is important to shift periodically the links at the fairlead so that additional fatigue damage due to bending can be more evenly distributed. If this procedure is part of the field operation plans, fatigue damage for the links around the fairlead can be evaluated based on the fraction of time when the links are located at the fairlead. However, the links at the fairlead should have sufficient fatigue strength to survive at least a single extreme VIM event (for example, the 100-year VIM event).

Mooring systems subjected to VIM can also experience increased wear in the links at the fairlead, which is caused by high contact pressure and large movement between links. This issue should be carefully evaluated, and the measure of periodically shifting the links at the fairlead should be considered to alleviate the wear problem. Wear measurement using go-no-go gauge as outlined in API 2I can also be considered for detecting excessive chain link wear.

8.4 Mooring line response

8.4.1 General

The floating structure dynamic response excites the mooring system in three distinct frequency bands:

— mean response;

— low-frequency responses;

— wave-frequency responses.

The extreme values of mooring line tension shall be evaluated combining these three contributions in accordance with 8.5. Extreme values of grounded lengths shall be evaluated in the same way, where applicable.

The responses of a mooring system to mean actions can be predicted by static elastic catenary equations, including line elongations. Generally, the responses to low-frequency motions can also be predicted by the same method because of the long periods of these motions. The responses of the mooring system to wave-frequency structure motions can be predicted by the methods given in 8.4.2 and 8.4.3.

8.4.2 Quasi-static analysis

In this approach, the wave actions are taken into account by statically offsetting the structure by wave-induced motions. Dynamic actions on the mooring lines associated with mass, damping and fluid acceleration are neglected. Research in mooring line dynamics has shown that the reliability of mooring designs based on this method can vary widely depending on the structure type, water depth and line configuration.

8.4.3 Dynamic analysis

Dynamic analysis of the mooring lines accounts for the time-varying effects due to mass, damping and fluid acceleration. In this approach, the time-varying fairlead motions are calculated from the structure's surge, sway, heave, roll, pitch and yaw motions. Dynamic models are used to predict mooring line responses to the fairlead motions.

Either the frequency-domain approach, 8.3.1.2, or the time-domain approach, 8.3.1.3, can be used to predict dynamic mooring tensions. In the time-domain approach, all non-linear effects including line elongation, line geometry, fluid loading, and sea floor effects can be modelled. The frequency-domain approach, on the other

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hand, is generally linear. Methods for approximating non-linearities in the frequency domain and their limitations should be investigated to ensure acceptable solutions for the intended application.

8.5 Line tension

8.5.1 Mean tension

The mean tension is the line tension corresponding to the mean offset of the structure response.

8.5.2 Extreme values of tension

When the frequency-domain approach is used to simulate structure response, 8.3.1.2, the extreme values of the line tension are obtained from the wave-frequency line tensions computed with the structure at positions equivalent to $S_{max} - S_{wfmax}$, with respect to each anchor location. The extreme values of line tension are then defined as

$$T_{extreme} = T_{static} \pm T_{wfmax} \tag{10}$$

where

$T_{extreme}$ is the extreme value of tension, in newtons, (N);

T_{static} is the static tension at $S_{extreme} - S_{wfmax}$, in newtons, (N);

T_{wfmax} is the maximum tension from frequency-domain analysis, in newtons, (N);

$S_{extreme}$ is the applicable value of S_{max} or S_{min} for the individual upper-terminal-point-to-anchor offset, from Equation (2) or Equation (3), respectively, in metres, (m);

S_{wfmax} is the upper-terminal-point-to-anchor offset defined in 8.2.3, in metres (m).

Alternatives to this approach are the time-domain approach, 8.3.1.3, and the combined time and frequency-domain approach, 8.3.1.4, which involve statistical processing of simulated time histories to yield maximum values of line tensions.

8.5.3 Design checks

Extreme line tension values shall be checked against the design criteria given in 10.2.

8.5.4 Tension for fatigue analysis

Line tension ranges for fatigue analysis are computed in analogy with 8.5.1 and 8.5.2. Details of the method are given in 9.3.3.2.

8.6 Line length and geometry constraints

Depending on the type of mooring system deployed, the type of anchors used and the mooring line material, a number of line length and geometry parameters shall be evaluated and assessed for compliance with design criteria.

For catenary moorings with drag anchors not specifically designed to withstand uplift, the minimum length of grounded line (always resting on the sea floor) shall be computed, and compared with a design criterion to be prescribed on a site-specific basis.

For anchors designed to withstand uplift forces, compliance with the appropriate design criteria for the specific anchor type shall be demonstrated.

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For some types of mooring lines, prolonged resting on the sea floor is highly undesirable and the portion of the line closest to the anchor is typically replaced by chain. In such cases, the minimum elevation of the line-to-chain connection shall be computed, and verified against a minimum elevation criterion to be prescribed on a site-specific basis.

For some types of mooring lines, exposure to the splash zone or to friction against the fairleads is also undesirable and the upper portion of the line is typically replaced by chain. In such cases, the position of the upper termination shall be evaluated and compared with a minimum depth criterion to be prescribed on a site-specific basis.

For mooring lines in proximity to other underwater and surface installations, other clearance requirements and geometric constraints can exist. In such cases, the analysis results for the displacements at the particular points of concern shall be verified against applicable design criteria, see 10.7, or be prescribed on a site-specific basis.

Line length and geometry constraints for synthetic fibre rope lines are presented in Clause 14.

8.7 Anchor forces

The larger of the extreme tensions from the mooring analysis specified in 8.5.2 shall be used to predict maximum anchor forces. The results shall be compared with the design criteria given in 10.4, as applicable.

8.8 Typical mooring configuration analysis and assessment

8.8.1 Frequency-domain analysis for spread mooring systems

In a mooring analysis using a frequency-domain description of the structure response, the mean position of the structure is first determined from static equilibrium calculations in surge and sway directions and yaw rotation. The surge, sway and yaw responses to wave and low-frequency excitations are then calculated and added to the mean position. The procedure outlined in A.8.8.1 should be used.

Where the floating structure has a small water plane area (see 8.2.2) alternative procedures incorporating all six degrees-of-freedom should be used.

8.8.2 Frequency-domain analysis for single point mooring systems

To perform an analysis based on a frequency-domain description of the structure response, assumptions on the structure's heading shall be made. The design headings at which the mooring system responses are calculated should be determined taking into consideration the mean equilibrium heading and low-frequency yaw motions. The procedure outlined in A.8.8.2, which is likely to yield a conservative approximation, should be used.

8.8.3 Time-domain analysis

Time-domain methods may be used to perform coupled simulations of mean response, low-frequency response and wave-frequency response for the combined system consisting of the structure and moorings. This approach requires a time-domain mooring analysis tool, which solves the general equations of motion to yield the combined mean, low and wave-frequency responses of the structure, mooring lines and risers. Significant advantages of this approach are that low-frequency damping from the structure, mooring lines and risers are internally generated in the simulation, and that coupling between the structure and the mooring/riser system is fully accounted for. The procedure is presented in A.8.8.3.

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8.9 Thruster-assisted moorings

8.9.1 General

The following subclauses deal with the particular configuration where a single point mooring system or a spread mooring system is assisted by onboard thrusters.

8.9.2 Analysis conditions

Intact and redundancy check definitions for thruster-assisted moorings (TAM) are given in Table 2 below.

Table 2 — Intact and redundancy check TAM definitions

TAM definition	Mooring system condition	Thruster system condition
Intact	Intact	Intact
Redundancy check	Intact	Redundancy check
Redundancy check	Redundancy check	Intact

8.9.3 Determination of allowable thrust

When thrusters are used to assist the mooring system, the allowable thrust to be used in the mooring analysis shall be determined as follows.

a) Determine the available effective thrust, taking into consideration the efficiency of the thrusters and losses due to floating structure motions, current, thruster/hull and thruster/thruster interference effects, and any directional restrictions.

b) Determine the worst thruster system failure. FMEA should be performed to identify the worst single failure, see 13.2.1. The definition of the worst single failure should allow for thruster system availability (mean time to failure and mean time to repair) over the design service life of the installation.

c) Determine the allowable thrust:

   1) for automatic thruster control systems, the allowable thrust shall be either

      i) for the intact thruster condition, equal to the available effective thrust, or

      ii) for the redundancy check thruster condition, equal to the available effective thrust after accounting for the worst failure as determined by the FMEA;

   2) for manual thruster control systems, the allowable thrust shall be 0,7 of the value found in 1).

The allowable thrust used in the mooring analysis should be verified during thruster system sea trials.

8.9.4 Load sharing

8.9.4.1 General

In a TAM system, load sharing between the thruster and the mooring systems is complex. However, the simple mean load reduction method described below yields reasonable results.

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8.9.4.2 Mean load reduction method

In this simplified approach, the thrusters are assumed to counter only the mean environmental actions in the surge, sway and yaw directions. Allowable thrusts from thrusters are first evaluated, see 8.9.3, and then subtracted from the mean action. The remainder of the mean action and the wave and low-frequency motions shall be sustained by the mooring system.

For structures with spread moorings, where the floating structure heading is held stable by the mooring lines, the surge and sway components of the allowable thrust can be subtracted from the mean surge and mean sway environmental actions. The mooring response shall then be evaluated using the analysis procedure for mooring systems without thruster assistance, see 8.8.1 to 8.8.3.

8.9.4.3 Heading control and surge damping

For structures with single point moorings, the main function of the thrusters is heading control. For structures with high thruster capacity that significantly exceeds the heading control requirements, the available capacity may be shared between heading control and the generation of low-frequency surge damping.

8.9.4.4 System dynamic analysis

A system dynamic analysis should be performed in the time domain. This model should generate the mean offset, low-frequency structure motions, control system characteristics and thruster responses corresponding to specific environmental conditions.

8.10 Transient analysis of floating structure motions

8.10.1 General

A moored floating structure experiences transient motions after a mooring line breakage or thruster system failure before it settles about a new equilibrium position, see 8.1.2.4. Transient analysis shall be performed to check the maximum offset resulting from such events, in accordance with Table 1.

Transient analysis of a moored structure under wind, wave, current and thruster actions is complex and can require a time-domain solution. To simplify the analysis, a combined approach may be used as described in 8.10.2.

8.10.2 Combined time and frequency-domain analyses

In this approach, the maximum transient motion is first determined using a time-domain analysis. The structure low and wave-frequency motions obtained from a frequency-domain analysis are then combined with the transient motions. The recommended procedure is as follows.

a) Compute the equilibrium position under mean actions for the intact mooring.

b) Simulate a line breakage and compute the maximum transient motion (overshoot) in the time domain with mean load only, but with the mooring system stiffness updated at each time step. Generally, a model with three degrees-of-freedom (surge, sway and yaw) is required.

c) Determine maximum structure offset by

$$S_{max} = S_{mean} + S_{lfsig} + S_{wfsig} + S_t \tag{11}$$

where

S_{mean} is the mean offset as calculated in step a), in metres (m);

S_{lfsig} is the positive value of significant low-frequency motion, calculated in the frequency domain using the redundancy check mooring system stiffness, in metres (m);

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S_{wfsig} is the positive value of significant wave-frequency motion, calculated in the frequency domain, in metres (m);

S_t is the maximum transient motion (overshoot) with respect to the equilibrium position from step a), as determined in step b), in metres (m).

8.10.3 Time-domain analysis

Time-domain transient analysis is similar to the structure response time-domain analysis described in 8.3.1.3. The only difference is that a mooring line is removed during the simulation to model a line breakage. The simulation should be repeated for a number of wave action time histories and for the break to occur at different time steps for each time history. The maximum offset observed during these simulations, or the maximum offset estimated from the results of these simulations, see 8.3.2, should be used.

9 Fatigue analysis

9.1 Basic considerations

Fatigue assessment is a complex process with many uncertainties. Typical fatigue analysis procedures are presented herein. Alternative procedures may be used, provided they can be documented to achieve similar levels of reliability to those presented herein.

Miner's Rule shall be used to determine accumulated fatigue damage. For the main components of mooring lines (i.e. chain, wire rope and connecting links), Miner's Rule calculations may be based on tension range (the so-called T-N approach) as described below, or on the stress range (the so-called S-N approach) as described in A.9.1. For other components, such as anchor piles and attachments, the S-N approach is generally used.

Time- and/or frequency-domain dynamic analyses shall be used to determine tension or stress ranges. A quasi-static analysis may be used only if it can be fully documented to achieve levels of reliability similar to those obtained with the time and/or frequency-domain dynamic analyses. Tank model test data may be used in lieu of dynamic analyses provided these data are fully documented as being suitable for fatigue analysis.

The determination of the fatigue resistance of some typical mooring system components is specified in 9.2. The fatigue resistance of synthetic fibre rope is discussed in Clause 14.

Calculation procedures for the determination of tension range cycles are given in 9.3. Several approaches for determining fatigue damage, involving varying degrees of simplification in the damage summation by the Miner's Rule, are given.

9.2 Fatigue resistance

9.2.1 Wire rope, chain and connecting links

The fatigue resistance of wire rope, chain, connecting links and other mooring system components is given by T-N curves, where the tension range, T, is usually non-dimensionalized by dividing by a suitable reference breaking strength and N is the permissible number of cycles. T-N curves shall be based on fatigue test data for these components and a regression analysis.

Representative T-N curves for some wire rope, chain and connecting links are given in 9.2.2. T-N curves shall be used to assess tension-tension (T-T) fatigue conditions according to 9.2.3. Bending-tension (B-T) and free bending fatigue conditions are addressed in 9.2.4.

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9.2.2 T-N curves

The equation for the representative T-N curve is

$$N\,T^m = K \tag{12}$$

where

N is the number of permissible cycles of tension range ratio, T;

T is the ratio of tension range (double amplitude) to the reference breaking strength of the component (the appropriate reference strength for each type of component is given below);

m is the inverse slope of the T-N fatigue curve;

K is a constant.

T-N curves plot as straight lines on log-log paper.

Values for m and K are given in Table 3 for a limited selection of chain link, connecting link and wire rope components.

Table 3 — Values of m and K for representative T-N curves

Component	m	K
Common studlink	3,00	1 000
Common studless link	3,00	316
Baldt and Kenter connecting link	3,00	178
Six / multi-strand wire rope (corrosion protected)	4,09	$10^{(3,20 - 2,79\,Q)}$ = 231, when Q = 0,3
Spiral strand wire rope (corrosion protected)	5,05	$10^{(3,25 - 3,43\,Q)}$ = 166, when Q = 0,3
NOTE Q is the ratio of mean tension to MBS of the wire rope.		

The reference breaking strength for R3, R4, and R4S common or connecting links is equal to the minimum breaking strength (MBS) of ORQ (Oil Rig Quality) common chain link of the same diameter.

To allow for the effects of corrosion and wear when determining the reference breaking strength of R3, R4, and R4S common or connecting links, the diameter should be taken equal to the nominal diameter minus half of the corrosion and wear allowance.

Table 3 indicates that the fatigue resistance of studless chain is less than that of the corresponding studlink chain. However, the presence of studs introduces a number of possible fatigue issues that cannot be detected by inspection (i.e. loose stud, stud weld crack, sharp corners at stud footprint, corrosion between stud and link, and defects hidden behind the stud). The equation for studlink chain is not valid for links with loose studs. Consequently, it is important to consider all factors affecting fatigue resistance in the selection of chain type.

The T-N curve for Baldt and Kenter connecting links is based on limited fatigue test data.

On the basis of limited fatigue data, the fatigue resistance of D-shackles is comparable to that of common links of the same size and grade, provided the shackle is machined to fit with close tolerance, no cotter pin is used through the shackle body, and the shackle is of the narrow throat type.

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For other types of connecting links, where published data are insufficient to generate fatigue resistance curves, appropriate tests shall be performed to establish such curves prior to the use of such links in permanent mooring systems. The tests shall be performed in a manner consistent with the tests on which the T-N curves listed in Table 3 are based.

The reference breaking strength for wire rope is equal to its MBS.

The T-N curves for wire rope are based on fatigue test data for six-strand, multi-strand and spiral strand rope. As shown in Table 3, wire rope fatigue resistance is a function of the mean tension in the rope which, in a catenary mooring system, is typically 0.2 to 0,3 of MBS. The fatigue assessment of wire rope shall account for the effect of mean tension according to 9.3.3.

The wire rope fatigue data are based on tests in which the effects of corrosion have been excluded. The T-N curves in Table 3 are therefore only appropriate for wire ropes protected from corrosion by, for example, galvanizing, sheathing, blocking compound and zinc filler wires. When using wire rope as part of permanent mooring systems, the design service life, inspection, and change out strategy should all be considered when determining the combination of corrosion protection systems needed for a specific application.

9.2.3 Tension-tension (T-T) fatigue

Chain, connecting link and wire rope components of mooring systems subjected to tension only shall be designed on the basis of fatigue resistance determined in accordance with 9.2.2 for the fatigue damage calculated in accordance with 9.3.3. The fatigue assessment of other mooring system components subjected to pure tension that can be designed using T-N curves should also be conducted in accordance with 9.2.2 and 9.3.3, provided appropriate T-N curves exist or can be developed.

9.2.4 Bending-tension (B-T) and free bending fatigue

Combined bending-tension of wire rope and chains generally occurs at locations such as fairleads, bending shoes, chain stoppers, hawser pipes, bend-limiting devices, and adjacent to clump weights and mid-water buoys. At these locations, tension-tension fatigue damage is aggravated by the presence of bending as well as by the additional possible effects of wear and corrosion.

In the absence of suitable data on the fatigue damage due to bending-tension on wire ropes, the bend diameter to rope diameter ratio should be large enough to avoid excessive bending, see Table A.4.

Fatigue analysis of wire rope and chains shall adequately account for the additional stress concentration at points of direct contact. Fatigue damage under such conditions can be alleviated by a combination of regular inspection and adjustment of the line so as to avoid concentrated bending at one location.

Free bending at wire rope terminations can induce significant fatigue damage and reduce fatigue life. Bend-limiting devices should be incorporated at such locations. Such devices shall be designed to smoothly transfer forces from the termination to the rope over the full range of structure draft and offset conditions.

9.3 Fatigue analysis procedure

9.3.1 General

The line tension calculation procedure for fatigue analysis is given in 9.3.3.2. Recommended fatigue analysis procedures are described in 9.3.2 and 9.3.3, while the fatigue safety factor is given in 10.5.

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9.3.2 Cumulative fatigue damage

The total fatigue damage during the design service life, L, is assumed to be equal to L times the annual fatigue damage. The annual fatigue damage in a mooring line component shall be determined as the sum of the annual fatigue damage arising in a combination of n mooring design states (MDSs). Each MDS consists of

— a directional sea state chosen to discretize the long-term environment to which the mooring system is subjected,

— a probability of occurrence of the sea state,

— a mean offset and heading representing the effects of the sea state, with associated wind and current, and

— representative loading conditions (i.e. draft conditions) of the floating structure.

The annual fatigue damage shall be computed as

$$D = \sum_{i=1}^{n} D_i \tag{13}$$

where

D is the annual fatigue damage in a mooring line component, years^{-1};

D_i is the annual fatigue damage arising in MDS$_i$, years^{-1}.

The discretization into i = 1, …, n combinations should take into account the sensitivity of the fatigue calculation to the assumed input parameters, including the effects of

— variation in direction of resultant mean environmental action,

— significant wave height,

— spectral peak period or mean zero-crossing period,

— spectral peakedness,

— mean floating structure offset (due to slow drift, current or other effects),

— hydrodynamic damping due to current or slow drift motion,

— expected range of current profiles with depth, and

— floating structure loading conditions.

9.3.3 Fatigue damage assessment

9.3.3.1 General

Once an appreciation of the overall configuration and the influence of environmental input data noted in 9.3.2 have been established, representative data for each MDS shall be selected and documented as the basis of the long-term fatigue assessment. Each environmental condition shall be defined in terms of the wind, wave and current parameters and their directions. Floating structure loading conditions shall be identified in terms of draft, trim and heel (corresponding to a particular distribution of storage and ballast).

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The annual probability of occurrence, P_i, of MDS$_i$ shall be defined. Typically, eight to twelve directions should be considered as representing the directional distribution of the long-term environment. A sensitivity assessment, as described in 9.3.2, can be used to identify the number of sea states needed for an adequate long-term representation — typically 10 to 50. Normally, three floating structure loading conditions should be sufficient: floating structure fully loaded, fully ballasted and a representative long-term "mean" operating condition. If the mooring system operates in different modes, for example, with and without a structure attached, a separate analysis for each mode shall be performed.

The annual fatigue damage accumulated in an individual MDS shall be computed as

$$D_i = \left[\sum_k \frac{n_k}{N_k} \right]_i \tag{14}$$

where

n_k is the number of cycles of the non-dimensional tension range T_k occurring in MDS$_i$, per year;

N_k is the number of permissible cycles for non-dimensional tension range T_k from Equation (12), per year;

T_k is the non-dimensional tension range, as defined in 9.2.2.

The number of tension range cycles per year in each MDS can be determined as

$$n_i = f_i X_i = f_i \cdot P_i \cdot C_1 \tag{15}$$

where

f_i is the zero up-crossing frequency of the tension spectrum in MDS$_i$, in hertz;

X_i is the time spent in MDS$_i$ per annum, s;

P_i is the probability of occurrence of MDS$_i$;

C_1 is the average number of seconds per annum = 3,15576 × 10^7 s.

NOTE A simplified formulation of Equation (14) is presented in A.9.3.3.1, where T_k follows a Rayleigh distribution and the T-N curve is consistent with the form of Equation (12).

9.3.3.2 Tension range calculation

When performing frequency-domain analysis, the standard deviation of low-frequency tension shall be calculated about the mean floating structure offset for each MDS, i.e.

$$s_{\text{lf_eff}} = T_{\text{lf_mean + stdev}} - T_{\text{mean}} \tag{16}$$

where

$s_{\text{lf_eff}}$ is the effective standard deviation of the low-frequency tension, in newtons (N);

$T_{\text{lf_mean + stdev}}$ is the tension at $S_{\text{mean}} + s_{\text{lf_s}}$, in newtons (N);

T_{mean} is the tension at the mean offset, in newtons (N);

S_{mean} is the mean structure offset, in metres (m), as defined in 8.2.2;

$s_{\text{lf_s}}$ is the standard deviation of low-frequency motion of the upper-terminal-point-to-anchor offset, for each line, in metres (m).

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The standard deviation of wave-frequency tension shall also be calculated about the mean floating structure offset for each MDS.

When performing time-domain analysis, the time history of the tension can be directly derived from the analysis.

9.3.3.3 Combining wave-frequency and low-frequency tensions

9.3.3.3.1 General

For fatigue damage assessment, the following four methods can be considered for combining the damage due to wave-frequency and low-frequency tensions.

a) Simple summation: wave-frequency damage and low-frequency damage are calculated independently and the total damage is taken as the sum of the two.

b) Combined spectrum: the standard deviations of wave-frequency tension ranges and low-frequency tension ranges are calculated independently based on the separate wave-frequency and low-frequency tension spectra or the separate wave-frequency and low-frequency tension time series; the standard deviation of the combined response is computed using Equation (19). The damage is then calculated using the combined standard deviation.

c) Combined spectrum with dual narrow-banded correction factor: a correction factor is applied to the result of the combined spectrum method presented in b).

d) Time-domain cycle counting: fatigue damage is calculated from a tension time history using a cycle counting method, such as the rainflow method, to estimate the magnitude and number of tension range cycles. The tension time history can be determined directly by a time-domain analysis or it can be generated from the combined low and wave-frequency spectral analyses.

The relative merits of each of these methods are as follows.

— Method a), simple summation, is in principle non-conservative, but may be applied to a MDS if the low-frequency tension contribution to the total tension response is negligible [λ_{Li} < 0,15, see Equation (21)].

— Method b), combined spectrum, is generally conservative and may be applied to any MDS.

— Method c), combined spectrum with dual narrow-banded correction factor, is an improvement that yields less conservative predictions than method b), and that may also be applied to any MDS. However, the improvement tends to be lost in a MDS where the low-frequency tension is strongly dominant.

— Method d), time-domain cycle counting, if rigorously performed with sufficient number of time simulations representative of the wave scatter diagram, is generally considered to be the most accurate method of calculating fatigue damage and should be used when time history of the combined low-frequency and wave-frequency tension is available.

Analysis procedures for methods a), b) and c) are presented in 9.3.3.3.2 to 9.3.3.3.4.

9.3.3.3.2 Simple summation

The annual fatigue damage D_i for state MDS_i shall be determined by separate application of Equations (14) and (15) to wave-frequency and low-frequency tension ranges. The result is given in Equation (17):

$$D_i = \frac{n_{Wi}}{K}\left(2\sqrt{2}\sigma_{Wi}\right)^m \times \Gamma\left(1+\frac{m}{2}\right) + \frac{n_{Li}}{K}\left(2\sqrt{2}\sigma_{Li}\right)^m \times \Gamma\left(1+\frac{m}{2}\right) \quad (17)$$

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where the symbols are as defined in 9.2.2. Symbols with subscript Wi relate to the tensions for MDS$_i$ relative to wave-frequency excitation only, while symbols with subscript Li relate to the tensions for MDS$_i$ due to low-frequency excitation only, and where

n_{Li} is the number of low-frequency tension range cycles per year for MDS$_i$ from Equation (15) in which the average zero up-crossing frequency can be estimated by $1/t_n$, where t_n is the natural period (surge, sway and/or yaw as appropriate) of the moored structure computed at its mean position;

n_{Wi} is the number of wave-frequency tension cycles per year for MDS$_i$ from Equation (15);

σ_{Li} is the ratio of the standard deviation of low-frequency tension variations around the mean tension to the reference breaking strength;

σ_{Wi} is the ratio of the standard deviation of wave-frequency tension variations around the mean tension to the reference breaking strength;

Γ is the Gamma function.

K and m are defined in 9.2.2.

NOTE The standard deviation of the tension range probability distribution is twice the standard deviation of tension.

9.3.3.3.3 Combined spectrum

The annual fatigue damage D_i for state MDS$_i$ shall be determined as follows, based on a Rayleigh distribution of tension peaks:

$$D_i = \frac{n_i}{K}\left(2\sqrt{2}\sigma_i\right)^m \times \Gamma\left(1+\frac{m}{2}\right) \tag{18}$$

where

σ_i the ratio of the standard deviation of the combined wave and low-frequency tension variations around the mean tension to the reference breaking strength

$$\sigma_i = \sqrt{\sigma_{Wi}^2 + \sigma_{Li}^2} \tag{19}$$

n_i is the number of tension range cycles per year for MDS$_i$ from Equation (15) in which the average zero up-crossing frequency of the combined spectrum is given by

$$f_{Ci} = \sqrt{\lambda_{Wi} f_{Wi}^2 + \lambda_{Li} f_{Li}^2} \tag{20}$$

f_{Wi} is the zero up-crossing frequency of the wave-frequency tension spectrum in MDS$_i$, in hertz (Hz);

f_{Li} is the zero up-crossing frequency of the low-frequency tension spectrum in MDS$_i$, (calculated as described under n_{Li} in 9.3.3.3.2), in hertz (Hz);

$$\lambda_{Li} = \frac{\sigma_{Li}^2}{\sigma_{Li}^2 + \sigma_{Wi}^2} \tag{21}$$

$$\lambda_{Wi} = \frac{\sigma_{Wi}^2}{\sigma_{Li}^2 + \sigma_{Wi}^2} \tag{22}$$

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9.3.3.3.4 Combined spectrum with dual narrow-banded correction factor

The annual fatigue damage for state MDS_i shall be determined from

$$D_i = \rho_i \frac{n_i}{K}\left(2\sqrt{2}\sigma_i\right)^m \times \Gamma\left(1+\frac{m}{2}\right) \tag{23}$$

where

$$\rho_i = \frac{f_{ei}}{f_{Ci}}\left[\left(\lambda_{Li}\right)^{\left(2+\frac{m}{2}\right)}\left(1-\sqrt{\frac{\lambda_{Wi}}{\lambda_{Li}}}\right)+\sqrt{\pi\lambda_{Li}\lambda_{Wi}}\,\frac{m\Gamma\left(\frac{1+m}{2}\right)}{\Gamma\left(1+\frac{m}{2}\right)}\right]+\frac{f_{Wi}}{f_{Ci}}\left(\lambda_{Wi}\right)^{\frac{m}{2}} \tag{24}$$

f_{ei} is the mean up-crossing frequency of the envelope of the normalized tension variations around the mean tension

$$f_{ei} = \sqrt{\lambda_{Li}^2 f_{Li}^2 + \lambda_{Li}\,\lambda_{Wi}\,f_{Wi}^2\,\delta_{Wi}^2} \tag{25}$$

δ_{Wi} is the bandwidth parameter for the wave-frequency component of the normalized tension variations around the mean tension, which may be taken as equal to 0,1.

Values of the gamma function for some typical values of m are given in Table 4.

Table 4 — Gamma functions

m	3,00	4,09	5,05
$\Gamma\left[1+\frac{m}{2}\right]$	1,329	2,086	3,417
$\Gamma\left[\frac{1+m}{2}\right]$	1,000	1,373	2,047

9.3.3.4 Accounting for mean value of tension in wire rope

Fatigue damage in wire rope depends on the mean value of the tension as well as on the time-varying component. To account for this dual effect the mean tension shall first be determined for each mooring line in each MDS. From Table 3, the corresponding representative T-N curve shall then be selected to calculate the fatigue damage for that MDS. This implies that in principle a different representative T-N curve is applicable for each mooring line in each MDS.

10 Design criteria

10.1 Floating structure offset

Floating structure offset limits shall be established by clearance requirements and limitations on the satisfactory performance of equipment such as umbilicals, risers and gangways, and the time required for the safe operation of any disconnect system. Generally, different criteria apply to intact, redundancy check and transient motion conditions and these are detailed below.

The offset of the floating structure from the sea floor well location shall be controlled to prevent damage to drilling, well intervention or production risers.

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10.2 Line tension limit

For a mooring component, a tension limit should be expressed as a percentage of its MBS after reductions for corrosion and wear.

Tension limits for various conditions and analysis methods shall be set in accordance with Table 5, in which design safety factors are also listed. These limits apply only to properly maintained moorings and systems in which the connecting components have MBS greater than or equal to that of the mooring lines.

The same mooring line tension limits apply to TAM, provided that the thruster system is designed to an appropriate level of reliability and is capable of making a significant contribution to the stationkeeping capacity of the floating structure.

Table 5 — ULS line tension limits and design safety factors

Analysis condition	Analysis method	Line tension limit (percent of MBS)	Design safety factor
Intact	Quasi-static	50 %	2,00
Intact	Dynamic	60 %	1,67
Redundancy check	Quasi-static	70 %	1,43
Redundancy check	Dynamic	80 %	1,25
Transient	Quasi-static or dynamic	95 %	1,05

10.3 Grounded line length

If drag anchors are used, the outboard mooring line length shall be sufficient to prevent anchor uplift under any of the conditions covered by 8.1.2.5, unless it can be demonstrated that the anchor has sufficient vertical resistance. Guidance on the use of drag anchors to resist vertical forces is provided in A.10.4.2.

Shorter grounded line lengths may be used for moorings with anchoring systems that can resist substantial vertical uplift such as anchor piles, suction caissons, or anchors with demonstrably adequate vertical resistance.

10.4 Anchoring systems

10.4.1 General

The options that are available for anchoring floating structures include

— drag anchors,

— anchor piles (driven, jetted, suction, torpedo (gravity-embedded) and drilled and grouted), and

— other anchor types such as gravity anchors and plate anchors.

In selecting anchor options, consideration should be given to required system performance, soil conditions, reliability, installation and the test load. The structural strength of anchors should be demonstrated to be adequate with respect to the required foundation capacities.

10.4.2 Drag anchors

The ultimate holding capacity of a drag anchor represents the maximum horizontal component of the steady pull that can be resisted by the anchor at continuous drag. This includes the soil resistance on the buried portion of the chain or of the wire rope, but excludes the friction of the chain or wire rope lying on the sea floor.

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For typical mooring applications and soil conditions (i.e., homogeneous soft to medium stiff clay), the larger of the extreme mooring line tensions shall not exceed the ultimate holding capacity divided by the design safety factor given in Table 6.

Table 6 —ULS drag anchor holding capacity design safety factors

		Quasi-static analysis	Dynamic analysis
Permanent mooring	Intact condition	N/A	1,50
	Redundancy check	N/A	1,00
Mobile mooring	Intact condition	1,00	0,80
	Redundancy check	Not required	Not required

The factors in Table 6 do not necessarily apply to drag embedded plate anchors, which are further discussed in A.10.4.4.2.1.4.

10.4.3 Anchor piles

The representative vertical and horizontal resistances of anchor piles should be determined in accordance with the requirements for fixed steel structures, as applicable. The vertical and horizontal components of the larger of the extreme mooring line tensions derived from dynamic analysis shall not exceed the representative resistances divided by the design safety factors given in Table 7.

Table 7 — ULS design safety factors for holding capacity of anchor piles and suction piles

	Permanent mooring		Mobile mooring	
Analysis condition	**Axial loading**	**Lateral loading**	**Axial loading**	**Lateral loading**
Intact condition	2,00	1,60	1,50	1,20
Redundancy check	1,50	1,20	1,20	1,00

10.4.4 Other anchor types

Design criteria for gravity anchors and plate anchors are given in Table 8. Other anchor types may be deployed provided they can be documented to achieve similar levels of reliability to the anchors discussed in Tables 6, 7 and 8. Design safety factors are defined as anchor capacity from the failure envelope divided by extreme values of the anchor forces from dynamic analysis.

Table 8 — ULS design safety factors for holding capacity of gravity and plate anchors

	Gravity anchor				Plate anchor	
	Permanent mooring		Mobile mooring		Permanent mooring	Mobile mooring
Analysis condition	**Axial loading**	**Lateral loading**	**Axial loading**	**Lateral loading**		
Intact condition	2,00	1,60	1,50	1,20	2,00	1,50
Redundancy check	1,50	1,20	1,20	1,00	1,50	1,20

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10.4.5 Chain and wire rope holding capacity

The holding capacity from friction of chain and wire rope on the sea floor may be estimated using:

$$F_{cw} = C_f \, l_{cw} \, W_{cw} \tag{26}$$

where

F_{cw} is the chain or wire rope holding capacity, in newtons (N);

C_f is the coefficient of friction between chain or wire rope and the sea floor;

l_{cw} is the length of chain or wire rope in contact with the sea floor, in metres (m);

W_{cw} is the submerged unit weight of chain or wire rope, in newtons per metre (N/m).

10.4.6 Mooring test load

10.4.6.1 General

All moorings shall be subject to load testing prior to initial use and again after any substantive change to the mooring configuration, whether by intent or by some natural or accidental event. The purpose of load testing is to ensure adequate holding capacity of the anchoring system, eliminate slack in the grounded portion of the mooring lines, and allow detection of any significant installation-induced damage to mooring components. The requirements for such test loads shall be defined by the designer in accordance with the following subclauses. Further details on test loading of suction and plate anchors are provided in A.10.4.6.1.

Note that the mooring test load should also be set high enough such that the additional drag to resist the design intact actions does not overload neighbouring lines. This is further discussed in A.10.4.2.1, A.10.4.2.10 and A.10.4.2.11.

10.4.6.2 Permanent moorings

For mooring lines with drag anchors, the test load magnitude in soft clay where deep anchor penetration can be achieved shall be equal to at least 80 % of the force induced by the environmental design situation as determined by a dynamic analysis of the intact condition (see A.10.4.6.2). In hard, sandy, or layered soils, where anchor penetration can be limited to no more than one fluke length, the test load magnitude shall be higher, and should be 100 % or more of the force induced by the environmental design situation as determined by a dynamic analysis of the intact condition. In defining the test load, the designer should consider the uncertainties in the calculated force and the consequences of potential platform displacement resulting from anchor movement.

For mooring lines with fixed anchors, e.g. anchor piles, the test load magnitude shall be sufficient to ensure the correct setting of the mooring line assembly and to ensure that the inverse catenary is sufficiently formed to prevent unacceptable mooring line slacking due to additional cut-in of the inverse catenary during storm conditions.

The duration of the installation test load shall be at least 15 min.

Note that that installation tension should also be set high enough such that the additional drag to resist the design intact actions does not overload neighbouring lines. This is further discussed in A.10.4.2.1, A.10.4.2.10 and A.10.4.2.11.

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