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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

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

ICS: 75.180.10

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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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The committee responsible for this document is ISO/XXX

This second/third/... edition cancels and replaces the first/second/... edition (), [clause(s) / subclause(s) / table(s) / figure(s) / annex(es)] of which [has / have] been technically revised.

ISO XXXX consists of the following parts. [Add information as necessary.]

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

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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 third edition cancels and replaces the second edition (ISO 19901-7:2013), which has been technically revised.

This third edition of ISO 19901-7 includes several changes. The largest changes are the deletion of informative sections related to geotechnical design of anchors to incorporate the same in 19901-4 and the inclusion of OPB fatigue guidance.

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*
- *Part 8: Marine soil investigations*
- *Part 9: Structural integrity management (under preparation).*

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 (all parts), *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units*
- ISO 19906, *Petroleum and natural gas industries — Arctic offshore structures*

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 and flotels) and construction units (such as heavy lift vessels and pipelay units).

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

- mooring systems (e.g. spread moorings or single point moorings);
- dynamic positioning systems (generally consisting of thrusters);
- a combination of mooring system and thrusters (thruster assisted)

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.

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 any combination of:
 - 1) production,
 - 2) storage,
 - 3) offloading,
 - 4) drilling and well intervention.
- b) the assessment of stationkeeping systems for site-specific applications of mobile offshore units and construction 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 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. << Sec 13.7 of 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 19901-4, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 4: Geotechnical and foundation design considerations*

ISO 19901-6, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 6: Marine operations*

ISO 19901-8, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 8: Marine soil investigations*. ISO 19904-1, *Petroleum and natural gas industries — Floating offshore structures — Part 1: Monohulls, semi-submersibles and spars*

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*

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 19900:2013]

3.2 action effect

effect of actions on structural components

[ISO 19900:2013]

¹⁾ Under preparation.

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 19900:2013]

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 19900:2013, definition 2.7.

3.5

common mode/common cause failure:

failure of similar components on different mooring legs resulting from the same direct cause, occurring within a relatively short time, where these failures are not consequences of another

3.6

damage event

event-driven damage to mooring components including physical damage, overload, excessive bending, etc., often experienced during the installation phase.

3.7

degradation mechanisms

time-based physical or chemical mechanisms or processes by which mooring components degrade. Examples are corrosion, wear, fatigue, etc.

3.8

design criteria

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

[ISO 19900:2013]

3.9

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 19900:2013, definition 2.12.

3.10

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 19900:2013, definition 2.13.

3.11

disconnectable floating structure

floating structure capable of discontinuing production and rapidly disconnecting from its ancillary components such as risers, moorings, and/or well systems in response to the occurrence or to the detection of a threshold event.

3.12**dynamic action**

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

3.13**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

3.14**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

3.15**failure causes**

includes the initiators, defects, processes and mechanisms generating damage or degradation which are the basic reasons for failure, and may be introduced into the mooring system across all phases of the mooring system lifecycle from design to operation.

3.16**failure mode**

the manifestation of loss of functionality of a mooring component and it is the manner by which failure is observed

3.17**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 19900:2013]

3.18**floating structure**

structure where the full weight is supported by buoyancy

[ISO 19900:2013]

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

3.19**limit state**

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

[ISO 19900:2013]

3.20**maintenance**

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

3.21**minimum breaking strength****MBS**

RCS certified strength of a chain, wire rope, fibre rope or accessories

3.22

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)

NOTE Some components of a mobile mooring system might not be retrievable and should be designed following the requirements of permanent mooring system.

3.23

mobile offshore drilling unit

MODU

structure capable of engaging in drilling and well intervention operations for exploration or exploitation of subsea petroleum resources

3.24

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.

3.25

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.

3.26

owner

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

3.27

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)

3.28

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.

3.29

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

3.30**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.

3.31**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]

3.32**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.

3.33**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.

3.34**serviceability**

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

3.35**significant value**

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

3.36**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.

3.37**ship-shaped structure**

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

3.38**spar platform**

deep-draught, small water-plane area floating structure

3.39**splash zone**

part of a structure that is intermittently exposed to air and immersed in the sea

NOTE Herein the relevant structural parts are mooring lines, fairleads and thrusters.

[ISO 19900:2013]

3.40

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

3.41

stationkeeping system

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

3.42

structural component

physically distinguishable part of a structure

[ISO 19900:2002]

3.43

structure

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

[ISO 19900:2002]

3.44

taut-line mooring

mooring system where the restoring action is provided by elastic deformation of mooring lines

[ISO 19900:2002]

3.45

thruster-assisted mooring

stationkeeping system consisting of mooring lines and thrusters

3.46

touchdown point

location on a mooring line where the line transitions from contacting the seabed to being in the water column

NOTE The touchdown point can change as the draught and horizontal offset of the floating structure change.

3.47

touchdown zone

set of all touchdown points within defined operating conditions

EXAMPLE The extent of the touchdown zone could be specified based on 100 year return period environmental conditions along with minimum and maximum floating structure draughts

3.48

verification

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

3.49

weathervaning

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

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)

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
MPM	most probable maximum
ORQ	oil rig quality
QTF	quadratic transfer function
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

5 Overall considerations

5.1 General requirements

General requirements in ISO 19900 shall be complied with.

5.2 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.

5.3 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.

Guidance on the conduct of formal risk assessments is to be found in References^{[152], [153]} and^[154].

Specific guidance on Stationkeeping systems hazards and risk assessment are given in A.5.3.2 and in Reference ^[151].

5.4 Planning requirements

5.4.1 General

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 5.2. The initial planning shall include the determination of all conditions and criteria, in accordance with the general requirements and conditions specified in ISO 19900.

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. For mobile offshore units, planning requirements are defined in ISO 19905-3. For construction units, planning requirements are defined in ISO 19901-6.

5.4.2 Design basis

At the outset of the design process, a document (design basis) shall be created to summarize

- definition of design practices and applicable standards, regulations, codes;
- definition of site-specific data such as seabed topography, geohazards, soil conditions and environmental conditions, including ice, as appropriate;
- applicable limit states, design situations and design criteria (see ISO 19900);
- fabrication, transportation and installation philosophy;
- inspection, monitoring, maintenance and repair philosophy including any the intervention strategy and availability of spares ;
- service and operational philosophy, and;
- mooring system removal philosophy.

5.4.3 Design Practises

Codes, standards, RCS rules, and regulations (collectively referred to as “standards” hereafter) applicable to the design, manufacturing, construction and installation of the stationkeeping system shall be clearly identified at the commencement of the project.

For innovative stationkeeping systems, or applications of unproven structural concepts where limited or no direct experience exists, appropriate analyses and testing shall be performed to demonstrate that the inherent safety level of the design is no lower than the safety level implicit in this part of ISO 19901 when applied to traditional structural forms or concepts.

5.4.4 Inspection, Monitoring, Maintenance and Repair Philosophy

At the planning stage, a philosophy for inspection and maintenance shall be developed and documented, to ensure full consistency with the design basis of the stationkeeping system and its components. The requirements for monitoring, sparing philosophy, residual capacity and emergency repair plan, , corrosion control, and inspection planning shall be consistent with the design service life of the floating structure established as part of the planning activities.

Any requirements for residual capacity, i.e., a design situation characterizing the stationkeeping system in a temporary impaired state after a single mooring line breakage or a failure of one or more thrusters as appropriately assessed by the FMEA, should be addressed at planning stage considering:

- the requirements to continue operations or site specific activities,
- the anticipated time required to perform the relevant repair or replacement based on the actual emergency response preparedness (availability of spares, marine spread, procedures etc.,)
- the national regulations.

A critical assessment shall be made of the ability of the stationkeeping system to achieve the intended inspection, monitoring, maintenance and repair objectives. Relevant provisions related to inspection, monitoring, maintenance and repair requirements are given in Clause 12.

5.5 Rules and regulations

The owner, in conjunction with the national regulator where one exists, shall identify the complete list of standards, which are regulatory documents, contractual agreements and company specifications whose requirements shall be met, clarifying areas of possible overlap and specifying the level of precedence in the enforcement of such requirements. <aligned with 19904-1 & 19900:2013>>

5.6 Independent verification

For permanent mooring, independent verification that the stationkeeping system design, manufacturing and installation is in compliance with the provisions of this part of ISO 19901 should be carried out as a combination of independent calculations, document reviews and audits, surveys and inspections, etc., as appropriate.

Verification activities should demonstrate that the design, manufacturing and installation processes are adequate. The scope and extent of the verification carried out, the procedures employed, and relevant reports should become part of the integrity management system.

The above requirements may be satisfied in part, or in full, by classing the stationkeeping system by an RCS. <<P Smedley- is this required? revisit, adding requirement for verification for permanent mooring systems. >>

5.7 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

GeneralThe definition of the exposure level for floating structures is given in ISO 19900.

6.1.1 Exposure levels for stationkeeping systems

The exposure level assigned to a permanent stationkeeping system in any operating mode 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: <<to confirm with WG5 if to modify in line with new 19900 definitions>>

- 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,
- stationkeeping system operating modes including temporary phases during installation and operation such as storm safe, offloading, disconnected situation for a disconnectable turret,
- 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.

6.4 Design situations

6.4.1 General

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.

a. Permanent mooring

For permanent moorings, the design situations detailed below apply to mooring systems for floating structures with an L1 exposure level — see ISO 19900 for the definition of exposure levels.

b. For mobile mooring

For mobile mooring the determination of the assessment situation shall be based on the considerations given in ISO 19905-3. <<19905-3 refers to L2, and refers back to 19901-7. Need to clarify- can we remove references to exposure levels altogether? Alain – prefers to remove, >>

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.

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. Two ULS design situations have to be considered for this purpose:

- a) The mooring system is connected to the floating structure, the parameters characterizing the ULS design situation are defined without accounting for the adverse environmental event leading to the disconnection (eg. non-cyclone extreme)

- b) The mooring system is dis-connected from the floating structure and the ULS design situation is defined according to a accounting for the adverse environmental event if relevant

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.

In certain cases it can be acceptable to continue operating with the unit in an impaired state (e.g. with a single line damaged) if suitable analysis shows such a condition meets all the requirements of this part of ISO 19901, including the requirement for an additional mooring line damaged case, and the remaining lines are not susceptible to a common mode failure.

6.4.2.2.6 Permanent moorings during installation

Design situations for temporary phases during the installation of a permanent mooring shall be in accordance with the requirements of ISO 19901-6.

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 if the likelihood of impact from loss of position, free drift of the floating structure, or excessive drag of anchors on a surface or sub-surface asset is very low.

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.

In certain cases it can be acceptable to continue site-specific activities with the unit in an impaired state (e.g. with a single line damaged) if suitable analysis shows such a condition meets all the requirements of this part of ISO 19901, including the requirement for an additional mooring line damaged case.

6.4.2.3.4 Mobile moorings with long term deployment

Components of a mobile mooring that cannot be subjected to a close visual inspection and NDT within the stipulated inspection schedule shall be designed to meet the requirements of 6.4.2.2.

6.4.2.3.5 Mobile moorings with short term deployment

Provisions of ISO 19901-6 apply to short term deployment of mobile mooring systems for construction vessels such as heavy lift vessels and pipelay vessels.

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.

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 8.3.3 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 for permanent mooring designed for disconnection. 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, hurricanes or cyclones, vessel collision, generic failure, complete black-out leading to non-availability of thrusters. Design situations for ALS may also arise from a formal risk assessment linked to the functional and safety requirements in 5.1 and 5.3 or local regulations.

Robustness of the system should be checked beyond ULS design conditions. Such an assessment may identify a bad behaviour or a weak point in the system that could lead to catastrophic failure of the stationkeeping system.

Accidental events with return periods in excess of 10,000 years may be neglected.

For permanent mooring systems designed for disconnection, an appropriate ALS design situation consists of the adverse environmental event combined with a failure to safely disconnect in that environmental event. The probability of failure disconnection shall be based on quantitative reliability analysis combined with the FMEA of the disconnection system.

If the joint probability of occurrence of the adverse environmental event combined with the failure to disconnect is less than 10^{-4} per annum, ALS design check is not required.

6.4.6 Design situations for temporary phases

6.4.6.1 General

Consideration should be given to define appropriate design situations for temporary phases i.e., phases significantly shorter than design life and/or that can be weather restricted. The effects of design situations applicable to temporary phases shall be addressed during design to avoid exceedance of either ULS or SLS criteria, and to assess contributions to FLS.

6.4.6.2 Storm safe situation

The storm safe situation is the temporary phase where the minimum number of mooring lines required to make the floating structure safe against environmental actions exceeding installation criteria. Environmental design conditions during this temporary phase shall normally be taken as a minimum of one year return period (See 19904-1 Sec A.6.4.6). This condition may take account of seasonal effects but should normally not be taken as being less than a two month seasonal span. <<overlap between 19901-6 & 19904-1. If leaving for longer period, refer to 19901-6>>

6.4.6.3 Offloading

For floating structures that are intended to be offloaded directly to a tanker, the environmental design conditions for the assessment of the stationkeeping system should be taken as a minimum one year return period.

6.4.6.4 Degraded situation

For a floating structure to continue site-specific activities with its stationkeeping system in an impaired state (e.g. with a single line/thruster failure), the following requirements shall be met:

- the stationkeeping system in the impaired condition meets the ULS line tension limits of this part of ISO 19901, under environmental actions of return period defined in Table 2, 19901-6, and

Example: including the requirement for redundancy check (e.g. another mooring line failure) <<HOLD, return period, reword..return period based on risk analysis.>>

- the failure was not the result of a common mode of failure or error that can lead to other stationkeeping components failing under non-extreme conditions.
- a risk assessment of the stationkeeping system is performed to taking into consideration the status of the system to ascertain the impact of the mooring failure on surface and sub-surface assets, extreme offsets and clearances.

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, swell, wind and current data shall be collected sufficient to satisfy 6.4.4. Relative directionality between wind, wave, swell and current and resultant heading shall be considered for the fatigue analysis.

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

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 seafloor conditions

Seafloor soil conditions shall be investigated for the intended site to provide data for the anchoring system design. Details about equipment and procedures for marine soil investigations are provided in ISO 19901-8.

To assist in the assessment of the corrosion and wear mechanisms, seafloor sediments should be characterised in terms of depth of sediment strata, their friction angle, undrained shear strength, particle size, Mohr hardness of loose sediment particles, organic content; presence of cemented or compacted substrates and their respective hardness and undrained shear strength, propensity for trenching under cyclic action by dynamic mooring lines. The seafloor slope shall be properly accounted for in the mooring analysis, when relevant. For permanent moorings a bottom survey shall be performed. Further guidance on geotechnical site investigation can be found in ISO 19901-4.

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.

For design against squall events, time series of wind direction and wind velocity should be recorded and used in a time domain simulation analysis. Considering the physics of the squall event, as a base case, the extreme wind shall be considered omni-directional unless otherwise demonstrated.

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.

7.2.9 Physicochemical parameters

Parameters influencing degradation mechanism such as corrosion should also be defined. Typically statistics of water temperature, dissolved oxygen and dissolved inorganic nitrogen at various water depths should be established.

7.3 Environmental actions on mooring lines

7.3.1 General

In this sub-clause, 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):

$$F = 1/2 \rho_w C_d \cdot d \cdot v^2 \quad (1)$$

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/m³);

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 and additional fatigue damage, 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 or semi-submersible platforms and large FPSOs 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.

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 validated 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. Wind pitch and roll moments can be 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).

The different riser configurations shall be accounted for in the estimation of current actions.

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 and the loading condition..

A heading analysis shall be conducted for a weathervaning structure to establish the equilibrium heading for the combination of non-collinear metocean conditions and loading condition assessed. The equilibrium heading depends on the relative magnitude and direction of wind, wave and current loading.

NOTE: The draught of the floating structure will affect the equilibrium heading and hence the whole operating range of the floating structure should be investigated to identify the most onerous loading condition on the mooring system.

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.

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.

7.4.8 Local Component Dynamics

Mooring lines can consist of a number of connected elements with different mass, axial stiffness, torsional stiffness and drag properties. The location of these components within the mooring line relative to end connections/fairleads and/or the seabed will influence the local dynamic response of these components. Similarly, the dynamic response of the mooring line will vary depending on whether it is on the windward or leeward side of the mooring system. The resultant local dynamic behaviour of a component or set of components can introduce undesirable behaviour into the system, leading to accelerated degradation. Degradation can take a number of forms including abrasion, wear, mechanical damage, compression loading or rotation of components outside of the design alignment.

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 8.9 for the intact, redundancy check and transient conditions as defined below. Descriptions of analysis conditions for thruster-assisted moorings are given in 8.10.2.

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.

8.1.2.5 Recommended analysis methods and conditions

The analysis methods (see 8.3.3) 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.			

<<DNV Recommends to delete SLS from the table, Alain, RK- leave>>

8.2 Actions considerations

8.2.1 General

All the actions to be considered in a mooring analysis are described in 7. The selection of analysis methodology shall consider each of these actions in order to evaluate the potential influence on the design. Since analysis assumptions and approximations may neglect some of these actions, it is necessary to check that the planned analysis methodology is suitable for the characteristics of the mooring system.

8.2.2 Non-linearities

The choice of the approach considered for the analysis is important to ensure the correct estimation of the environmental actions on mooring lines.

The frequency domain approach only allows linear and second order calculations. It is then necessary to linearize the non-linear actions to take them into account in the analysis. Justification of the validity of all the assumptions made for the linearization shall be performed and verified by adequate means.

The time domain approach allows to take into consideration non-linear effects. Even though this approach is usually more time-consuming, priority should be given to time domain simulations when non-linear actions have an important influence on the floating unit response.

8.2.3 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.

8.2.4 Riser considerations

The riser system (if any) interacts with the floating structure and the mooring system in several aspects. Consideration shall be given to imposed load on the floating structure from the environmental actions on risers. 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. However, 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 environmental actions on risers, riser stiffness and damping. Influence of asymmetry in riser configuration shall be considered in the mooring analysis matrix.

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.

The influence on the mooring system response may be ignored if doing so results in a more conservative mooring design.

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.

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 8.9.2.

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.

When assessing a weather-vaning mooring system under extreme squall event, time domain analysis shall be used.

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.

8.3.1.5 Model Test

Estimates of the mooring system response to be used for design can be obtained by model tests. Model tests can also be used either to calibrate analytical predictions or to determine responses not directly or reliably calculable. The objectives of such model tests shall be clearly defined (see A.8.3.3.1.2) and, because during tests extraordinary or unexpected behaviour can occur, consideration should be given to the provision of continuous monitoring equipment to record such behaviour.

When comparing the results of model tests with analytical predictions, the following potential sources of discrepancies should be considered.

- a) Scale effects, such as those affecting Reynolds number, fluid interface and turbulence.
- b) Viscous effects (Reynolds number-dependent fluid drag and lift components) in both model tests and analytical predictions.

NOTE In computer simulations, these coefficients can be varied in order to study their effects.

- c) Wave reflections from side walls induced by radiated and reflected incident waves.
- d) Limitations on the accuracy of modelling physical properties, parameters and dimensions.
- e) Limitations on the accuracy of the test results resulting from finite record lengths, finite sample rates, and numerical accuracy of the data analysis procedures.
- f) Assumptions made in the development of the numerical model.

NOTE An example is the assumption of linearity of the responses with respect to wave height, which is almost always made in the frequency domain analysis. This can cause significant discrepancies between the numerical and test results for very steep waves or in situations where viscous forces play an important role. In some cases, the instrumentation itself can affect the responses. The effect of instrumentation on the model should be minimized whenever possible.

8.3.2 Extreme value statistics

For time-domain analysis, relevant extreme values can be determined by one of the two methods outlined in A.8.3.2.

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):

$$V_{\text{sig}} = \pm 2s \quad (2)$$

$$E_{\text{max}} = +s\sqrt{2\log_e(t/t_z)} \quad (3)$$

$$E_{\text{min}} = -s\sqrt{2\log_e(t/t_z)} \quad (4)$$

where

V_{sig} is the significant value;

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

$$t_n = 2\pi\sqrt{M/k} \quad (5)$$

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 (3) 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 Vortex-induced motion considerations

8.3.3.1 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.8.3.3.1 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.

8.3.3.2 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 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.

8.3.3.3 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.

8.3.3.4 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 8.3.3.5) 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.

8.3.3.5 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.

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.

8.3.3.6 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 RP 2I can also be considered for detecting excessive chain link wear.

8.4 Floating structure offset

8.4.1 General

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

8.4.2 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.

8.4.3 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 (6) and (7).

$$S_{\max} = S_{\text{mean}} + \text{MAX} (S_{\text{dyn1}}, S_{\text{dyn2}}) \quad (6)$$

$$S_{\min} = S_{\text{mean}} - \text{MAX} (S_{\text{dyn1}}, S_{\text{dyn2}}) \quad (7)$$

$$S_{\text{dyn1}} = S_{\text{lfmax}} + S_{\text{wfsig}} \quad (8)$$

$$S_{\text{dyn2}} = S_{\text{wfmax}} + S_{\text{lfsig}} \quad (9)$$

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 8.11.2.

8.5 Mooring line response

8.5.1 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 8.6. 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 8.5.2 and 8.5.3.

8.5.2 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.

8.5.3 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 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.

8.6 Line tension

8.6.1 Mean tension

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

8.6.2 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 $S_{\max} - S_{\text{wfmax}}$, with respect to each anchor location. The extreme values of line tension are then defined as

$$T_{\text{extreme}} = T_{\text{static}} \pm T_{\text{wfmax}} \quad (10)$$

where

- T_{extreme} is the extreme value of tension, in newtons, (N);
- T_{static} is the static tension at $S_{\text{extreme}} - S_{\text{wfmax}}$, 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 8.4.3, 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.

8.6.3 Design checks

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

Consideration should also be given to the dynamic response of the lightly loaded legs within the mooring system, particularly where there are transitions between component types near or in the thrash zone. Compressive loading on wires and synthetic fibre rope (see 14.5.2) should be avoided.

8.6.4 Tension for fatigue analysis

Line tension ranges for fatigue analysis are computed in analogy with 8.6.1 and 8.6.2. Details of the method are given in 9.2.5.2.

8.7 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.

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.

The actual geometry of the line accounting for the effects of inverse catenary and trenching can affect the pre-tension and additional floating structure offset resulting from trenching or embedment of lines should be assessed at design stage. <<sensitivity study on line length/load sharing>>

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. Surface installations for checking clearances applicable for an external-turret moored unit include the hull of the floater itself.

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

8.8 Anchor forces

The larger of the extreme tensions from the mooring analysis specified in 8.6.2 shall be used to predict maximum anchor forces. The results shall be compared with the design criteria given in 10.4, as applicable.

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

$$F_{cw} = C_f l_{cw} W_{cw} \quad (11)$$

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).

The coefficient of friction depends upon the nature of the seafloor and on the type of mooring line. Static (starting) friction coefficients are normally used to compute the holding power of the line and sliding coefficients are normally used to compute the friction forces on the line during mooring deployment.

If more specific data are not available, for chain and wire rope the generalized coefficients given in Table 2 can be used for various sea floor conditions such as soft mud, sand, and clay. Guidance for calculation of the seabed friction is also provided in DNV-RP-E301^[37]. However, industry experience indicates that coefficients of friction can vary significantly for different soil conditions, and much higher values for the sliding coefficient of friction have been encountered.

Table 2 - Mooring line friction coefficients

Mooring line	Coefficient of friction f	
	Static	Sliding
Chain	1,0	0,7
Wire Rope	0,6	0,25

8.9 Typical mooring configuration analysis and assessment

8.9.1 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.8.9.1 should be used.

Where the floating structure has a small water plane area (see 8.4.2) alternative procedures incorporating all six degrees-of-freedom should be used.

8.9.2 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.8.9.2, which is likely to yield a conservative approximation, should be used.

8.9.3 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.8.9.3.

8.9.4 Combined time and frequency-domain analysis

In this 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. This method presents a good compromise between the accuracy of the results and the required computing time. However the compliance with all the assumptions is to be clearly stated. In particular, the LF responses of the unit are to be well separated from the wave frequency motion.

In this approach the mooring line model is usually quasi-static, since the dynamic effect of the line usually occur at wave frequency (or above) and could not be properly taken into account due to the determination of the wave frequency response by frequency-domain approach.

Two methods may be used to combine the frequency-domain solution to the mean and low-frequency responses:

- superimposition to time histories
- superimposition of statistical extreme values. In this approach, the mean response and the low-frequency response time histories are statistically analysed to determine the extreme values, which are then combined with the extreme values of the wave-frequency response to arrive at the maximum structure offset and line tension

Time histories of all main response parameters (structure displacements, mooring line tensions, anchor forces, etc.) obtained from the simulation shall be post-processed statistically to yield extreme values. The duration of the time-domain simulation should be long enough to yield stable statistical values.

8.10 Thruster-assisted moorings

8.10.1 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.

Thruster assistance can be utilised for:

- a) Mean Load Reduction (Constant Thrust)
- b) Provide stiffness and damping
- c) Line tension reduction or
- d) Heading Control (weathervaning units)

Depending on the mode of operation, the same moored unit with thruster assistance can utilise thrusters to fulfil any of the above described functions. Hence the analysis of a TAM system should reflect the mode of operation.

8.10.2 Analysis conditions

Intact and redundancy check definitions for thruster-assisted moorings (TAM) are given in Table 3 below.

Table 3 — 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

8.10.3 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.

- e) 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.
- f) 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.
- g) 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. Thruster capacity reduction due to degradation of the system or reduction in available power should be considered when evaluating available thrust to assist position mooring.

8.10.4 Load sharing

8.10.4.1 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 the most optimum results. Where capacities of the

TAM system is marginal, and consequences of a system failure is high, system dynamic analysis should be undertaken.

8.10.4.2 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 8.10.3, 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 8.9.1 to 8.9.3.

8.10.4.3 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.

8.10.4.4 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.

8.11 Transient analysis of floating structure motions

8.11.1 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 8.11.2.

8.11.2 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

$$S_{\max} = S_{\text{mean}} + S_{\text{lf sig}} + S_{\text{wf sig}} + S_t \quad (12)$$

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);
- 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).

8.11.3 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

The predominant loading on a mooring system is tension and global mooring analyses, such as those described in 8.6, are typically based solely on tension loading, i.e. tension-only element properties can be specified in global analyses. For mooring systems, the associated cyclic fatigue is defined as tension-tension (T-T) fatigue, and is detailed in 9.2.

In some situations significant local non-tensile cyclic loads, can arise which need to be accounted for in the fatigue assessment and , see 9.3.

- either through proper fatigue analysis such as tension-bending of top chain section (see 9.3)
- or through precautionary measures to control torsion <<and bending?>> in chain or free bending in wire ropes.

Relatively short sections of chain, wire rope or connecting links subject to complex loading should be assessed using an appropriate modelling method to determine representative actions, deformations and stress concentrations. Fatigue damage from these other sources of actions and restraints should be combined with the T-T fatigue damage (9.2.1) and appropriate factor(s) of safety applied (10.5).

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), damage calculations can be based on tension range (T-N approach, 9.2.2) or on stress range (the S-N approach, 9.2.3).

For other components, such as anchor piles and attachments to hull, the S-N approach is generally used (see 9.2.3).

The determination of the fatigue resistance of some typical mooring system components is specified in 9.2.2. Alternative calculation procedures and fatigue curves may be used, provided they can be documented to achieve similar levels of reliability to those presented herein.

The fatigue resistance of synthetic fibre rope is discussed in Clause 14.

Time- and/or frequency-domain dynamic analyses shall be used to determine tension ranges 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.

Fatigue assessment shall be performed for every component of a permanent mooring system or a mobile mooring that cannot be retrieved to conduct a close visual inspection or NDT within a stipulated time frame specified by RCS.

Calculation procedures for the determination of tension and stress range cycles are given in 9.2.4. Various approaches for determining fatigue damage, involving varying degrees of simplification in the damage summation by the Miner's Rule, are given in 9.2.5.3.

Fatigue assessment is a complex process with many uncertainties. It should be remembered that while the following design fatigue calculations and associated explicit safety factors in 10.5 have been derived to give similar notional reliability to other structural components and systems, historically, mooring lines have prematurely failed or degraded at a higher rate on-average. Consequently, the fatigue, corrosion and wear (10.6), design calculations in this Clause are only part of the process to ensure sufficient mooring reliability.

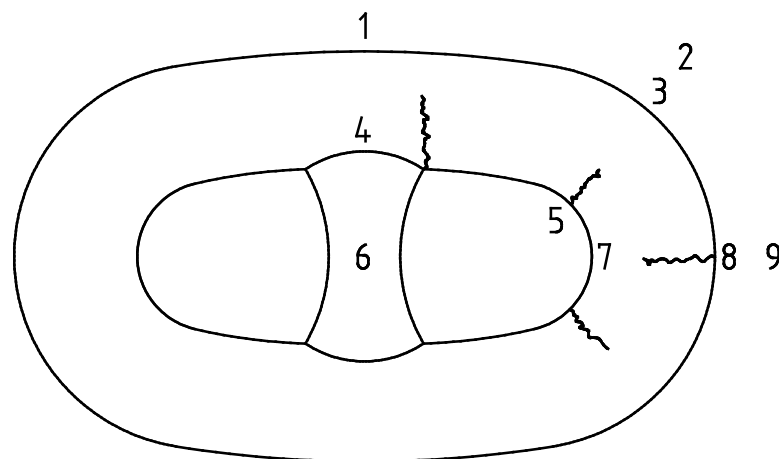
9.2 Tension-tension (T-T) fatigue

All mooring lines are subject to T-T loading, primarily from direct and indirect environmental actions (See 7). Chain has traditionally been considered a tension only system while, for wire rope, bending is minimised by maintaining high bend radii at touchdown points, pile and hull interfaces, etc., or introducing chain or connectors in these locations.

A representative number of fatigue tests have been performed and design T-N and S-N curves derived to enable in-service fatigue damage to be estimated. Consequently, chain, wire rope and connecting link components of mooring systems subjected to tension only shall be designed on the basis of fatigue resistance determined in accordance with 9.2.1 for the fatigue damage calculated in accordance with 9.2.4.

Under T-T fatigue, the chain link crack initiation and development hot spots are (see also Figure 1):

- The link intrados near the junction between the curved and straight link sections (4 per link).
- The link extrados at the crown (2 per link).
- The connection between the stud and the link in case of studlink chain



Key

1	Axial tension bending tension	6	STUD
2	Half crown	7	Comp
3	Compression	8	Tension
4	Axial tension bending comp	9	Crown
5	Tension		

Figure 1 T-T Fatigue failure locations for studlink chain^[88]

9.2.1 Fatigue resistance

The fatigue resistance of wire rope, chain, connecting links and other mooring system components is given by fatigue-life tension-tension (T-T) design curves, either:

- 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, or
- S-N curves, where the stress range, S , is the nominal stress range i.e. the tension range divided by a suitable nominal area and N is the permissible number of cycles.

T-N and S-N curves shall be based on a regression analysis of fatigue test data for these components in a representative environment.

Owner shall select an assessment based on either the T-N (9.2.2) or S-N (9.2.3) approaches or an alternative equivalent method.

Owner shall not select either the T-N or S-N approach based on a comparative assessment indicating the approach that provides the longer design life.

Fatigue calculations of chain and connecting links shall be based on the estimated section thickness at mid design life (or later) accounting for corrosion and wear (see 10.6).

The wire rope fatigue data are based on tests in which the effects of corrosion have been excluded. The fatigue curves for wire rope 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.

9.2.2 T-N curves for wire rope, chain and connecting links

The equation for the representative T-N curve is

$$N T^m = K \quad (13)$$

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.

Values for m and K are given in Table 4 for a limited selection of chain link, connecting link and wire rope components.

Table 4 — 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
Baldr and Kenter connecting link	3,00	178

Component	m	K
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 **any offshore grade common** or connecting links is equal to the minimum breaking strength (MBS) of ORQ (Oil Rig Quality) common chain link of the same diameter. The fatigue curves for wire rope are based on fatigue test data for six-strand, multi-strand and spiral strand rope. 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 9.2.5.

On the basis of limited fatigue data, the fatigue resistance of D-shackles is comparable to that of common links of the same nominal 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.

The T-N curve for Baldt and Kenter connecting links is based on limited fatigue test data. Baldt and Kenter connecting links shall not be used for permanent mooring **unless consequence of mooring system failure are assessed as limited (shallow water CALM Buoy). However fatigue curve is presented to permit fit-for-purpose fatigue assessment of such components in existing mooring lines arrangement.**

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 mooring chain T-N curves are based.

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

When using the T-N approach 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 4, the corresponding representative T-N shall then be selected to calculate the fatigue damage for that MDS. *This implies that in principle a different representative T-N or S-N curve is applicable for each mooring line in each MDS.*

9.2.3 S-N curves for wire rope, chain and connecting links

The nominal stress ranges, S (in Megapascals), are computed by dividing the corresponding tension ranges in Newton by the nominal cross-sectional area of the component, in square millimetres, i.e.

$$\frac{2\pi d^2}{4} \quad \text{for chain} \quad (14)$$

$$\frac{\pi d^2}{4} \quad \text{for steel wire rope} \quad (15)$$

where d is the component diameter, in millimetres (m). For chain, d is the diameter of the bar forming the chain link; for wire rope, it is the outside diameter of the wire bundle excluding any covering.

The relationship between the stress range (double amplitude), S , and the number of permissible cycles, N , of stress range S , follows an identical format to the T-N relationship given in Equation (13), i.e. the equation for the representative S-N curve is

$$N S^m = K \quad (16)$$

Values for m and K are given in Table 5 for a selection of chain link, connecting link and wire rope components in sea water.

Table 5 — m and K values for representative tension-tension S-N curves^[37]

Component	m	K
Stud chain	3,0	$1,2 \times 10^{11}$
Studless chain (open link)	3,0	$6,0 \times 10^{10}$
Six/multi-strand wire rope (corrosion protected)	4,0	$3,4 \times 10^{14}$
Spiral strand wire rope (corrosion protected)	4,8	$1,7 \times 10^{17}$

The fatigue life of other components (Subsea connectors, H-link etc.) can be calculated using the B1 curve according to DNV-RP-C203^[35] and appropriate stress concentration factors (SCF) obtained by a finite element method.

9.2.4 Fatigue analysis procedure

9.2.4.1 General

The line tension calculation procedure for fatigue analysis is given in 9.2.5.2. Recommended fatigue analysis procedures are described in 9.2.4.2 and 9.2.5, while the fatigue safety factor is given in 10.5.

9.2.4.2 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. draught conditions) of the floating structure.

The annual fatigue damage shall be computed as

$$D = \sum_{i=1}^n D_i \quad (17)$$

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 $i = 1, \dots, n$ 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.

9.2.5 Fatigue damage assessment

9.2.5.1 General

Once an appreciation of the overall configuration and the influence of environmental input data noted in 9.2.4.2 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 draught, trim and heel (corresponding to a particular distribution of storage and ballast).

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 9.2.4.2, 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

$$D_i = \left[\sum_k \frac{n_k}{N_k} \right]_i \quad (18)$$

where

- n_k is the number of cycles of the non-dimensional loading range (S_k or T_k) occurring in MDS_i , per year;
- N_k is the number of permissible cycles for non-dimensional tension range T_k or stress range S_k from Equation (12) or (13), per year;
- T_k is the non-dimensional tension range, as defined in 9.2.2.
- S_k is the stress range, as defined in 9.2.3

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

$$n_i = f_i X_i = f_i P_i C_1 \quad (19)$$

where

- f_i is the zero-up crossing frequency of the tension spectrum in MDS_i ;
- 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 = $3,15576 \times 10^7$ s

NOTE A simplified formulation of Equation (18) is presented in A.9.2.5.1, where T_k follows a Rayleigh distribution and the T-N or S-N curve is consistent with the form of Equation (13) or Equation (16).

9.2.5.2 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.

$$s_{lf_eff} = T_{lf_mean} + stdev - T_{mean} \quad (20)$$

where

s_{lf_eff}	is the effective standard deviation of the low-frequency tension, in newtons (N);
$T_{lf_mean} + stdev$	is the tension at $S_{mean} + s_{lf_s}$, 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 8.4.2;
s_{lf_s}	is the standard deviation of low-frequency motion of the upper-terminal-point-to-anchor offset, for each line, in metres (m).

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 (or the stress) should include the mean, low-frequency and wave frequency contributions.

9.2.5.3 Combining wave-frequency and low-frequency tensions

9.2.5.3.1 General

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

- Simple summation: wave-frequency damage and low-frequency damage are calculated independently and the total damage is taken as the sum of the two.
- 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 (24). The damage is then calculated using the combined standard deviation.
- Combined spectrum with dual narrow-banded correction factor: a correction factor is applied to the result of the combined spectrum method presented in b).
- 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 [$\lambda_{Li} < 0,15$, see Equation (26)].