OTC-26035-MS

Mooring of MRE Structures - Comparison of Codes, Including IEC

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This paper was prepared for presentation at the Offshore Technology Conference held in Houston, Texas, USA, 4–7 May 2015.

Abstract

Objectives/Scope

This paper presents guidance on the design and selection of mooring systems, including anchors, specifically for Marine Renewable Energy (MRE) systems. It is based in part on the work of the ASCE COPRI MRE Committee over the last five years. The document gives guidance to MRE designers and analysts and gives confidence as to mooring systems reliability.

Methods, Procedures, Process

There are a few MRE systems, especially for Wave Energy Converters (WECs) that have evolved, which may be regarded as having a basically similar mooring system. However, selection of design criteria, including environmental conditions return period (and other parameters) as well as safety factors for WEC moorings has not yet evolved into a standard procedure. This paper contrasts the mooring system characteristics that are found for some typical WEC moorings when their design is selected to meet various mooring codes and standards. Codes considered include those published by:

ISO
API
ABS
DNV
Lloyds
IEC (International Electrotechnical Commission)
US Navy

Results, Observations, Conclusions

Differences in the mooring codes are contrasted. Differences in the resulting mooring systems characteristics are contrasted resulting from using different codes. Differences in the systems are also contrasted with selection of different return periods and other environmental parameters. The results are also presented in the framework of the MRE Committee's approach to risk and reliability that has been developed by the oil and gas (O&G) industry over the last 40 years.

Novel/Additive Information

This paper presents an insight as to what is in the ASCE COPRI MRE guide for moorings

Introduction

International Electrotechnical Commission, IEC in 2014 prepared a (committee draft) technical specification for Assessment of Mooring Systems for Marine Energy Converters (MEC). This draft technical specification defines rules and assessment procedures for the design, installation and maintenance of mooring system with respect to technical requirements for floating marine energy converters. The IEC mooring technical specification is applicable to floating marine energy converters of any size in open water conditions.

The technical specification also normatively refers to existing and well established more detailed mooring codes. This paper compares the IEC mooring technical specification against other existing mooring codes to help designers navigate the MRE design in safe, reliable and economical manner.

Note that Marine Energy Converters (MECs) and Marine Renewable Energy Structures (MRE Structures) are used interchangeably in this paper.

System Description

Typical mooring system design including the anchors is discussed in this paper. A typical mooring system consists of mooring line, mooring line components, winching equipment and anchors. The mooring line components consist of connecting links, buoys, clump weight, wire rope socket etc.

IEC Technical Specification Overview

IEC technical specification uses limit state design and load resistance factor design (LRFD) as the design code for mooring analysis for MRE structures. The IEC technical specification refers to existing code for various design areas as shown in Table 1. The IEC technical specification is primarily referencing existing ISO 19901-7.

Table 1—IEC Mooring Technical Specification – Normative Reference Codes

Design and Engineering Area	Code Reference
Mooring Component Design	ISO 19901-7
Fatigue	ISO 19901-7
Anchor/Foundations	ISO 19901-7
Risk Assessment	API-RP-2SK, ISO 17776
Inspection, Monitoring, Testing and Maintenance	API-RP-2I

Comparison of Mooring Codes

The existing mooring codes considered for this paper and the overview of the scope of these codes is given in Table 2. The codes presented from left to right are in the order of assumed relevance for MEC mooring design. Other mooring codes for offshore structures exist such as Germanischer Lloyd (GL), [9], Lloyds Register (LR), [10] and US Navy, [27] but are not discussed in greater detail in this paper. Note also that ABS SPM Rules are not discussed.

Table 2—Mooring Codes and Scope Overview

Code	IEC DTS 62600-10	ISO 19901-7	API-RP-2SK	DNV-OS-E301	ABS FOTWI Guide	DNV-OS-J103	API-RP-2I	ISO 17776
Code Name	Assessment of mooring system for MECs	Station keeping of floating offshore structures	Station keeping systems for floating structures	Position Mooring	Floating offshore wind turbine install.	Design of floating wind turbine structures	In-service inspection of mooring hardware	Tools and techniques for hazard iden. and risk assessment
Year	2014	2004	2005	2010	2013	2013	2008	2010
Reference	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Mooring System	✓	✓	✓	✓	✓	✓	-	-
Tendons	-	-	✓	-	-	✓	-	-
Anchor Foundations	✓	✓	✓	✓	✓	✓	-	-
Attached Structures (riser, umbilical, etc.)	✓	✓	✓	✓	✓	✓	-	-
Mooring Inspection, Monitoring, Testing and Maintenance	✓	✓	✓	✓	✓	✓	✓	-
Risk Assessment	✓	-	✓	-	-	-	-	✓
Installation/Commission	✓	✓	✓	✓	✓	✓	-	-
Decommission	✓	-	-	-	-	-	-	-
Other Areas								
Wind Turbine	-	-	-	-	-	✓	-	-
Floating Structure	-	-	-	-	-	✓	-	-
Power Cable	✓	-	-	-	-	✓	-	-

Design Return Period

Structures are to be designed for environmental conditions of a given extreme return period. The environment design return period for IEC mooring code is given in Table 3. The design return period is consistent among all the codes reviewed. The probability for the extreme design conditions of 100 year return period is 1 x 10^{-4} /year. The probability of incidence of an extreme event increases with every year of service life as shown in Figure 1. To further understand the risk and reliability of the MREs, refer to the paper on risk and reliability of MREs, [14].

Table 3—Environment Return Period

Class	IEC
ULS	100 yr return period or higher
ALS	100 yr return period or higher
FLS	All conditions up to design return period for design life
SLS	As suitable for operations

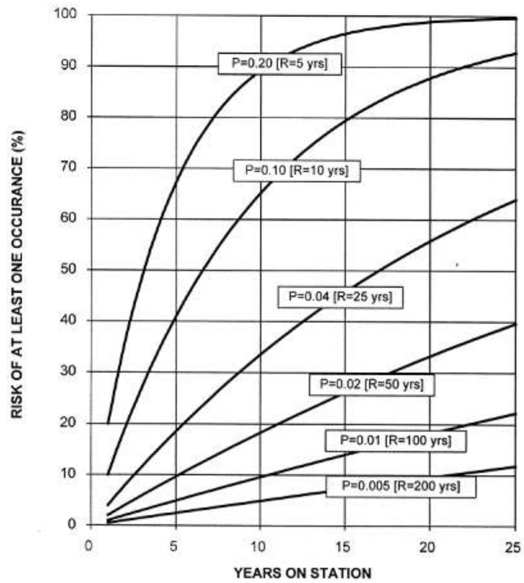

Figure 1—Risk of at Least One Return Period Event Occurrence during Service Life, [24]

Note that the return period environmental data for design of offshore structures is to be derived from measured data from relatively very short duration. For example, 100 year return period environment data is typically estimated from measured data over a period of 1 year to 10 years or sometimes even lesser durations. Extreme return period data must be acknowledged to be statistical in nature and may not be sufficiently rigorous, [25]. Therefore, 1000 year return period robustness checks are evaluated by O&G industry to assess the implications.

Consequence Class and Design Factors

Consequence class for a design will have to consider all consequences to life, environment, society and finances. Higher consequence requires higher design safety factor.

A preliminary guidance to determine the consequence class for the IEC mooring specification is given in Table 4. Comprehensive analysis by considering human life, environment and financial hazards should be undertaken to determine the consequence class. Comparison of the design factor as a function of consequence class for the IEC mooring specification is also given in Table 5.

Table 4—IEC Mooring Technical Specification – Consequence Class

	Consequence Class		
Life Safety Category	High	Medium	Low
Manned non-evacuated	3	3	3
Manned evacuated	3	2	2
Unmanned	3	2	1

Table 5—IEC Mooring Technical Specification – Design Factor by Consequence Class

Consequence Class	Design Factor
3	1.5
2	1.3
1	1.0

From the draft IEC document:

For consequence class 3, possible outcomes of a mooring system failure may include loss of human life, significant damage to marine environments, blockage of high traffic navigable waterways, and substantial financial or third party property damage.

For consequence class 2, possible outcomes of a mooring system failure may include serious injury, damage to marine environment, blockage of navigable waterway, and financial or property damage.

For consequence class 1, possible outcomes of a mooring system failure may include minimal human injury, minimal environmental impact, minimal navigable waterway impact, and minimal financial or property damage.

Mooring System Strength Design

Mooring lines should be designed to withstand the extreme tension loads for all loading conditions. The strength design factors will ensure certain level of safety of the mooring line. Comparison of strength design safety factors between various codes is given in Table 6. Similar comparison for LRFD codes is also given in Table 7. Assuming high safety class and dynamic to mean load ratio of 1:2, equivalent safety factors for LRFD code, DNV-OS-J102 are also evaluated in Table 6 for comparison.

Table 6—Mooring Line Strength – Design Factor of Safety

Design Condition	Type of Loading	IEC DTS 62600-10	ISO 19901-7	API-RP-2SK	DNV-OS-E301 (2)	DNV-OS-J103 (2)
Ultimate Limit State	Dynamic	1.67	1.67	1.67	1.63	1.73
	Quasi-static	2.00	2.00	2.00	-	-
Accidental Limit State	Dynamic	1.25	1.25	1.25	1.08	1.08
	Quasi-static	1.43	1.43	1.43	-	-
Transient (1)	Dynamic	-	-	1.05	-	-
	Quasi-static	-	-	1.18	-	-

Note (1) : Transient condition happens due to the overextension because of mooring failure or thruster failure. Factor of safety for transient condition is obtained from 2010 Vryhof manual, [11] and could not be verified with API-RP-2SK, [3].Note (2) : Factors provided are for indicative comparison of codes and SHOULD NOT be used for design. Factors are calculated conservatively for high safety class and assuming dynamic loads are 50% of the mean loads. The code design is LRFD and the associated partial safety factors are given in Table 7.

Table 7—Mooring Line Strength Design – LRFD Codes, Partial Safety Factors

Design Condition	Type of Loading/Safety Class	DNV-OS-E301 Normal	DNV-OS-E301 High	DNV-OS-J103 Normal	DNV-OS-J103 High
Ultimate Limit State	γ_{mean}	1.10	1.40	1.30	1.50
	γ_{dyn}	1.50	2.10	1.75	2.20
Accidental Limit State	γ_{mean}	1.00	1.00	1.00	1.00
	γ_{dyn}	1.10	1.25	1.10	1.25

Based on comparison of all codes, the strength design factors are comparable. The IEC codes also outlines that the mooring design factors for MECs may be updated with time as more data becomes available.

Fairleads, winches and their local supporting structures for fixed position of the mooring system shall withstand forces equivalent to 1.25 times the characteristic strength of any individual mooring line, [1]. API-RP-2SK recommends equal or higher design strength than mooring line, [3]. The IEC support structure design is consistent with other mooring codes.

Anchors or foundations design is of primary importance for a good mooring system design. Comparison of anchor holding capacity design safety factors between various foundations types are given in Table

8 below. The anchor foundation design is consistent among all reviewed codes. The proof load testing of anchors requirements such as tension magnitude and tension maintenance duration are found to vary considerably between codes, Table 9.

Table 8—IEC Anchor Holding Capacity Design – Factors of Safety

Mooring Type	Design Condition	Drag Anchor	Plate	Anchor/ Suction Pile/ Gravity Anchor – Axial Load	Anchor/ Suction Pile/ Gravity Anchor – Lateral Load
Permanent	Ultimate Limit State	1.5	2.0	2.0	1.6
	Accidental Limit State	1.0	1.5	1.5	1.2
Temporary	Ultimate Limit State	1.0 (1)	1.5	1.5	1.2
	Accidental Limit State	n/a	1.2	1.2	1.0

Note (1): Per API-RP-2SK and ISO19901-7, for the temporary ultimate limit state design of drag anchors the factor is 0.8.

Table 9—Tension Maintenance Durations

Code	API-RP-2SK	Lloyds	ABS	DNV
Reference	[3]	[10]	[28]	[4]
Tension Magnitude	80% of maximum mooring line load intact condition	To be assigned	80-100% of maximum mooring line load intact condition	50% of maximum mooring line breaking strength
Tension Maintenance Time (min)	15	20	30	15

A survey of anchors and foundations of the offshore O&G industry structures in varying water depths can be found in [24]. This information may serve as good go-by reference for existing designs of anchors and foundations. To further understand about the anchors and foundations, refer to the paper on anchors and foundations of MREs, [13].

Corrosion and Wear Allowance

Corrosion and wear allowance are important considerations for chain and wire mooring line design. Protection against chain corrosion and wear is normally provided by increasing the chain diameter. IEC code design considers wear allowance but no guidance is provided on the actual wear allowance values. Corrosion and wear allowance for chain is available in other mooring codes and are given in Table 10.

Table 10—Chain Corrosion and Wear Allowance (mm/year of Design Life)

Chain	IEC DTS 62600-10	ISO 19901-7	API-RP-2SK	DNV-OS-E301
Splash Zone	-	0.2 - 0.4	0.2 - 0.4	0.2 - 0.4
Thrash Zone (Seabed)	-	0.2 - 0.4	0.2 - 0.4	0.3 - 0.4
Away from Splash zone and thrash zone	-	0.1 – 0.2	0.1 – 0.2	0.2 – 0.3

Fatigue Design

The design fatigue life of the structure should be greater than the field service life by a factor of safety. The fatigue design should take into account the slow drift and wave motion components. The fatigue design for used mooring components should consider fatigue damage accumulated from previous operations.

Comparison of fatigue design safety factors between various codes is given in Table 11.

Table 11—Fatigue Design Factors of Safety for Metallic Components, Comparison Between Codes

Mooring Type	Parameter	IEC DTS 62600-10	ISO 19901-7	API-RP-2SK	DNV-OS-E301	ABS FOTWI Guide	DNV-OS-J103
Temporary	All Components	-	-	Not required	3	-	-
Permanent	Inaccessible Components	6	6	3	5 – 8 (1)	10	10
	Accessible Components	6	6	3	5 – 8 (1)	3	6

Note (1) –Safety factor is fatigue damage ratio dependent. Safety factor is 5.0 for fatigue damage ratio < 0.8. Safety factor greater than 5 for fatigue damage > 0.8
Note (2): All values given for chain and other metallic components. Rope design require different fatigue design safety factors

Go-by fatigue curve data for design of stud chain, studless chain (open link), stranded rope, spiral rope and polyester rope is given in ISO-19901-7 and DNV-OS-E301. The T-N fatigue data should be based on fatigue test data and used cautiously due to insufficient and non-representative test data. The lack low tension regime data and seawater conditions may make the test data non-representative.

Clearance

No clashing is allowed between any mooring component and other adjacent structure. The minimum clearance is to be defined based on consequence of the clashing. This is consistent among all codes reviewed, including IEC code.

Analysis Considerations

Coupled analysis is recommended if possible for mooring and MRE structure systems. All codes recognize coupled analysis to accurately predict the individual response of floating structure, mooring and associated structures (power cable, umbilical, riser etc.). All latest finite element analysis software packages such as ABAQUS, ANSYS, Flexcom, NREL FAST algorithm and OrcaFlex are capable of performing the coupled analysis.

Quasi-static approach should not be used for calculating tension ranges for fatigue analysis. The quasi-static approach is deficient in estimating wave frequency tensions. Time domain analysis or model testing may be utilized.

Operational Considerations: Inspection, Monitoring, Testing and Maintenance

All codes prescribe a rigorous and inspection regime within API-RP-2I, [7]. The rigorous and effective inspection of mooring hardware is required because mooring failures can result from corroded or physically damaged mooring components, defective connecting hardware, or mooring components of inferior quality. For further inspection considerations, refer to the MRE paper, [15]

The recommended monitoring parameters and the requirements among various codes are summarized in Table 12:

Table 12—Monitoring Requirements, Comparison, ACodes

Monitoring Parameter	IEC DTS 62600-10	ISO 19901-7	API-RP-2SK	DNV-OS-E301
Mooring Tension	✓	✓	✓	✓
Line Payout	✓	✓	✓	-
Floater Position	✓	✓	✓	-
Floater Heading/Orientation	✓	✓	✓	-

Ship impacts and collisions

IEC mooring technical specification addresses the mooring system design for collisions and consequences. DNV-OS-J103 addresses these design aspects in greater detail. This analysis should be considered by designers of MECs in areas of high marine traffic.

Mooring System Failures

Typical mooring design failures do not always follow the classical bath tub curve as shown in Figure 2.

The mooring system failures from the O&G industry, [12] are summarized below:

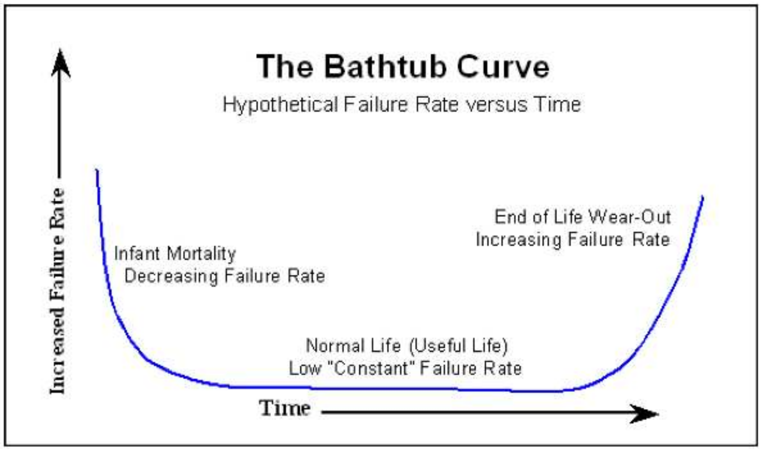

Figure 2—Typical Bathtub Curve

- Local scour at suction piles reducing the soil strength
- The offsets of the offshore structure may create trench around a suction pile anchor from mudline till chain anchor location on suction pile thus reducing the suction pile resistance, [18]
- Abrasion failure of synthetic ropes due to soil particles when in contact with seabed. This may happen when used especially for deepwater applications with large vessel excursions, [19], [20]
- Failure on deepwater chain link due to locking and out of plane loading in chain links, [21]
- Fatigue damage in dynamic components. Microbial induced corrosion can decrease the fatigue life, [22]
- Pitting corrosion can be severe with microbiological, [22]
- Corrosion as function of time may be difficult to design for, [23]
- Wireline corrosion and degradation of fatigue life
- Wireline birdcage damage due to seabed contact
- Thruster-assisted moorings (TAM) can have undesirable thruster response. If TAM is considered, all codes recommend that a comprehensive failure mode and effect analysis (FMEA) be performed.
- Design the mooring for transient loads due to failure of one (or two) mooring lines.

Based on the mooring failures from O&G industry, the failures mechanisms can be unexpected. The implications of mooring system failure can not only be very costly but also put the marine energy industry reputation at stake.

Conclusions

The IEC mooring technical specification is on par with other mooring subject matter codes available. A good mooring design should encompass the following aspects:

- Competent design with special attention to design environmental data
- Develop and document inspection, maintenance and monitoring philosophy at the planning stage
- Design and incorporate the inspection, maintenance and monitoring philosophy
- Quality control during manufacturing
- Integrity and serviceability throughout the service life

The IEC draft mooring technical specification emphases that the mooring design for MECs is in nascent stages. The IEC design factors may be updated with time as more data becomes available from existing and ongoing designs. Some existing MEC mooring design codes note that the mooring design of MECs is very similar to already existing mooring designs for oil and gas (O&G) industry. The available O&G codes and the O&G industry learnings can be taken advantage of for the design of MEC mooring systems.

The offshore structure mooring design learnings can be cross pollinated among various areas (O&G or renewable energy or others). The learnings may not be limited to just strength and fatigue design but also to the maintenance and failure mechanisms.

Based on O&G industry findings, following a particular code(s) in a prescriptive manner is not sufficient. The failure mechanisms (chaffing, microbial corrosion etc.) can be unexpected. Designing and quantifying for these unexpected mechanisms at times is difficult which may or may not be reflected in the design safety factors. Therefore, the mooring maintenance and operations should be supplement with inspection and maintenance to ensure safe and economical operations. A responsible design will help safe guard health, safety and environment and the reputation of all offshore industries.

Acknowledgements

We would like to thank all the industry mooring experts who contributed to the codes and industry learnings. We would also like to thank the entire marine renewable energy group and ASCE COPRI MRE Committee for the consistent work and passion for the effort to make the marine energy structures a safe and economic reality for securing energy future of the world.

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