Guidance for Long-term Hydro-structure Calculations

February 2019

Rule Note
NI 638 DT R00 E

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BUREAU VERITAS MARINE & OFFSHORE

GENERAL CONDITIONS

1. INDEPENDENCE OF THE SOCIETY AND APPLICABLE TERMS

1.1 The Society shall remain at all times an independent contractor and neither the Society nor any of its officers, employees, servants, agents or subcontractors shall be or act as an employee, servant or agent of any other party hereto in the performance of the Services.

1.2 The operations of the Society in providing its Services are exclusively conducted by way of random inspections and do not, in any circumstances, involve monitoring or exhaustive verification.

1.3 The Society acts as a services provider. This cannot be construed as an obligation bearing on the Society to obtain a result or as a warranty. The Society is not and may not be considered as an underwriter, broker in Unit's sale or chartering, expert in Unit's valuation, consulting engineer, controller, naval architect, designer, manufacturer, shipbuilder, repair or conversion yard, charterer or shipowner; none of them above listed being relieved of any of their expressed or implied obligations as a result of the interventions of the Society.

1.4 The Society only is qualified to apply and interpret its Rules.

1.5 The Client acknowledges the latest versions of the Conditions and of the applicable Rules applying to the Services' performance.

1.6 Unless an express written agreement is made between the Parties on the applicable Rules, the applicable Rules shall be the Rules applicable at the time of entering into the relevant contract for the performance of the Services.

1.7 The Services' performance is solely based on the Conditions. No other terms shall apply whether express or implied.

2. DEFINITIONS

2.1 "Certificate(s)" means classification or statutory certificates, attestations and reports following the Society's intervention.

2.2 "Certification" means the activity of certification in application of national and international regulations or standards, in particular by delegation from different governments that can result in the issuance of a Certificate.

2.3 "Classification" means the classification of a Unit that can result or not in the issuance of a classification Certificate with reference to the Rules. Classification is an appraisement given by the Society to the Client, at a certain date, following surveys by its surveyors on the level of compliance of the Unit to the Society's Rules or to the documents of reference for the Services provided. They cannot be construed as an implied or express warranty of safety, fitness for the purpose, seaworthiness of the Unit or of its value for sale, insurance or chartering.

2.4 "Client" means the Party and/or its representative requesting the Services.

2.5 "Conditions" means the terms and conditions set out in the present document.

2.6 "Industry Practice" means international maritime and/or offshore industry practices.

2.7 "Intellectual Property" means all patents, rights to inventions, utility models, copyright and related rights, trade marks, logos, service marks, trade dress, business and domain names, rights in trade dress or get-up, rights in goodwill or to sue for passing off, unfair competition rights, rights in designs, rights in computer software, database rights, topography rights, moral rights, rights in confidential information (including know-how and trade secrets), methods and protocols for Services, and any other intellectual property rights, in each case whether capable of registration, registered or unregistered and including all applications for and renewals, reversions or extensions of such rights, and all similar or equivalent rights or forms of protection in any part of the world.

2.8 "Parties" means the Society and Client together.

2.9 "Party" means the Society or the Client.

2.10 "Register" means the public electronic register of ships updated regularly by the Society.

2.11 "Rules" means the Society's classification rules and other documents. The Society's Rules take into account at the date of their preparation the state of currently available and proven technical minimum requirements but are not a standard or a code of construction neither a guide for maintenance, a safety handbook or a guide of professional practices, all of which are assumed to be known in detail and carefully followed at all times by the Client.

2.12 "Services" means the services set out in clauses 2.2 and 2.3 but also other services related to Classification and Certification such as, but not limited to: ship and company safety management certification, ship and port security certification, maritime labour certification, training activities, all activities and duties incidental thereto such as documentation on any supporting means, software, instrumentation, measurements, tests and trials on board. The Services are carried out by the Society according to the applicable referential and to the Bureau Veritas' Code of Ethics. The Society shall perform the Services according to the applicable national and international standards and Industry Practice and always on the assumption that the Client is aware of such standards and Industry Practice.

2.13 "Society" means the classification society **'Bureau Veritas Marine & Offshore SAS'**, a company organized and existing under the laws of France, registered in Nanterre under number 821 131 844, or any other legal entity of Bureau Veritas Group as may be specified in the relevant contract, and whose main activities are Classification and Certification of ships or offshore units.

2.14 "Unit" means any ship or vessel or offshore unit or structure of any type or part of it or system whether linked to shore, river bed or sea bed or not, whether operated or located at sea or in inland waters or partly on land, including submarines, hovercrafts, drilling rigs, offshore installations of any type and of any purpose, their related and ancillary equipment, subsea or not, such as well head and pipelines, mooring legs and mooring points or otherwise as decided by the Society.

3. SCOPE AND PERFORMANCE

3.1 Subject to the Services requested and always by reference to the Rules, the Society shall:

- review the construction arrangements of the Unit as shown on the documents provided by the Client;
- conduct the Unit surveys at the place of the Unit construction;
- class the Unit and enter the Unit's class in the Society's Register;
- survey the Unit periodically in service to note whether the requirements for the maintenance of class are met.

The Client shall inform the Society without delay of any circumstances which may cause any changes on the conducted surveys or Services.

3.2 The Society will not:

- declare the acceptance or commissioning of a Unit, nor its construction in conformity with its design, such activities remaining under the exclusive responsibility of the Unit's owner or builder;
- engage in any work relating to the design, construction, production or repair checks, neither in the operation of the Unit or the Unit's trade, neither in any advisory services, and cannot be held liable on those accounts.

4. RESERVATION CLAUSE

4.1 The Client shall always: (i) maintain the Unit in good condition after surveys; (ii) present the Unit for surveys; and (iii) inform the Society in due time of any circumstances that may affect the given appraisement of the Unit or cause to modify the scope of the Services.

4.2 Certificates are only valid if issued by the Society.

4.3 The Society has entire control over the Certificates issued and may at any time withdraw a Certificate at its entire discretion including, but not limited to, in the following situations: where the Client fails to comply in due time with instructions of the Society or where the Client fails to pay in accordance with clause 6.2 hereunder.

4.4 The Society may at times and at its sole discretion give an opinion on a design or any technical element that would 'in principle' be acceptable to the Society. This opinion shall not presume on the final issuance of any Certificate or on its content in the event of the actual issuance of a Certificate. This opinion shall only be an appraisal made by the Society which shall not be held liable for it.

5. ACCESS AND SAFETY

5.1 The Client shall give to the Society all access and information necessary for the efficient performance of the requested Services. The Client shall be the sole responsible for the conditions of presentation of the Unit for tests, trials and surveys and the conditions under which tests and trials are carried out. Any information, drawing, etc. required for the performance of the Services must be made available in due time.

5.2 The Client shall notify the Society of any relevant safety issue and shall take all necessary safety-related measures to ensure a safe work environment for the Society or any of its officers, employees, servants, agents or subcontractors and shall comply with all applicable safety regulations.

6. PAYMENT OF INVOICES

6.1 The provision of the Services by the Society, whether complete or not, involve, for the part carried out, the payment of fees thirty (30) days upon issuance of the invoice.

6.2 Without prejudice to any other rights hereunder, in case of Client's payment default, the Society shall be entitled to charge, in addition to the amount not properly paid, interests equal to twelve (12) months LIBOR plus two (2) per cent as of due date calculated on the number of days such payment is delinquent. The Society shall also have the right to withhold Certificates and other documents and/or to suspend or revoke the validity of Certificates.

6.3 In case of dispute on the invoice amount, the undisputed portion of the invoice shall be paid and an explanation on the dispute shall accompany payment so that action can be taken to solve the dispute.

7. LIABILITY

7.1 The Society bears no liability for consequential loss. For the purpose of this clause consequential loss shall include, without limitation:

- Indirect or consequential loss;
- Any loss and/or deferral of production, loss of product, loss of use, loss of bargain, loss of revenue, loss of profit or anticipated profit, loss of business and business interruption, in each case whether direct or indirect.

The Client shall defend, release, save, indemnify, defend and hold harmless the Society from the Client's own consequential loss regardless of cause.

7.2 Except in case of wilful misconduct of the Society, death or bodily injury caused by the Society's negligence and any other liability that could not be, by law, limited, the Society's maximum liability towards the Client is limited to one hundred and fifty per-cents (150%) of the price paid by the Client to the Society for the Services having caused the damage. This limit applies to any liability of whatsoever nature and howsoever arising, including fault by the Society, breach of contract, breach of warranty, tort, strict liability, breach of statute.

7.3 All claims shall be presented to the Society in writing within three (3) months of the completion of Services' performance or (if later) the date when the events which are relied on were first discovered by the Client. Any claim not so presented as defined above shall be deemed waived and absolutely time barred.

8. INDEMNITY CLAUSE

8.1 The Client shall defend, release, save, indemnify and hold harmless the Society from and against any and all claims, demands, lawsuits or actions for damages, including legal fees, for harm or loss to persons and/or property tangible, intangible or otherwise which may be brought against the Society, incidental to, arising out of or in connection with the performance of the Services (including for damages arising out of or in connection with opinions delivered according to clause 4.4 above) except for those claims caused solely and completely by the gross negligence of the Society, its officers, employees, servants, agents or subcontractors.

9. TERMINATION

9.1 The Parties shall have the right to terminate the Services (and the relevant contract) for convenience after giving the other Party thirty (30) days' written notice, and without prejudice to clause 6 above.

9.2 In such a case, the Classification granted to the concerned Unit and the previously issued Certificates shall remain valid until the date of effect of the termination notice issued, subject to compliance with clause 4.1 and 6 above.

9.3 In the event where, in the reasonable opinion of the Society, the Client is in breach, or is suspected to be in breach of clause 16 of the Conditions, the Society shall have the right to terminate the Services (and the relevant contracts associated) with immediate effect.

10. FORCE MAJEURE

10.1 Neither Party shall be responsible or liable for any failure to fulfil any term or provision of the Conditions if and to the extent that fulfilment has been delayed or temporarily prevented by a force majeure occurrence without the fault or negligence of the Party affected and which, by the exercise of reasonable diligence, the said Party is unable to provide against.

10.2 For the purpose of this clause, force majeure shall mean any circumstance not being within a Party's reasonable control including, but not limited to: acts of God, natural disasters, epidemics or pandemics, wars, terrorist attacks, riots, sabotages, impositions of sanctions, embargoes, nuclear, chemical or biological contaminations, laws or action taken by a government or public authority, quotas or prohibition, expropriations, destructions of the worksite, explosions, fires, accidents, any labour or trade disputes, strikes or lockouts.

11. CONFIDENTIALITY

11.1 The documents and data provided to or prepared by the Society in performing the Services, and the information made available to the Society, are treated as confidential except where the information:

- is properly and lawfully in the possession of the Society;
- is already in possession of the public or has entered the public domain, otherwise than through a breach of this obligation;
- is acquired or received independently from a third party that has the right to disseminate such information;
- is required to be disclosed under applicable law or by a governmental order, decree, regulation or rule or by a stock exchange authority (provided that the receiving Party shall make all reasonable efforts to give prompt written notice to the disclosing Party prior to such disclosure.

11.2 The Parties shall use the confidential information exclusively within the framework of their activity underlying these Conditions.

11.3 Confidential information shall only be provided to third parties with the prior written consent of the other Party. However, such prior consent shall not be required when the Society provides the confidential information to a subsidiary.

11.4 Without prejudice to sub-clause 11.1, the Society shall have the right to disclose the confidential information if required to do so under regulations of the International Association of Classifications Societies (IACS) or any statutory obligations.

12. INTELLECTUAL PROPERTY

12.1 Each Party exclusively owns all rights to its Intellectual Property created before or after the commencement date of the Conditions and whether or not associated with any contract between the Parties.

12.2 The Intellectual Property developed by the Society for the performance of the Services including, but not limited to drawings, calculations, and reports shall remain the exclusive property of the Society.

13. ASSIGNMENT

13.1 The contract resulting from to these Conditions cannot be assigned or transferred by any means by a Party to any third party without the prior written consent of the other Party.

13.2 The Society shall however have the right to assign or transfer by any means the said contract to a subsidiary of the Bureau Veritas Group.

14. SEVERABILITY

14.1 Invalidity of one or more provisions does not affect the remaining provisions.

14.2 Definitions herein take precedence over other definitions which may appear in other documents issued by the Society.

14.3 In case of doubt as to the interpretation of the Conditions, the English text shall prevail.

15. GOVERNING LAW AND DISPUTE RESOLUTION

15.1 These Conditions shall be construed and governed by the laws of England and Wales.

15.2 The Parties shall make every effort to settle any dispute amicably and in good faith by way of negotiation within thirty (30) days from the date of receipt by either one of the Parties of a written notice of such a dispute.

15.3 Failing that, the dispute shall finally be settled under the Rules of Arbitration of the Maritime Arbitration Chamber of Paris ("CAMP"), which rules are deemed to be incorporated by reference into this clause. The number of arbitrators shall be three (3). The place of arbitration shall be Paris (France). The Parties agree to keep the arbitration proceedings confidential.

16. PROFESSIONAL ETHICS

16.1 Each Party shall conduct all activities in compliance with all laws, statutes, rules, economic and trade sanctions (including but not limited to US sanctions and EU sanctions) and regulations applicable to such Party including but not limited to: child labour, forced labour, collective bargaining, discrimination, abuse, working hours and minimum wages, anti-bribery, anti-corruption, copyright and trademark protection, personal data protection (https://personaldataprotection.bureauveritas.com/privacypolicy).

Each of the Parties warrants that neither it, nor its affiliates, has made or will make, with respect to the matters provided for hereunder, any offer, payment, gift or authorization of the payment of any money directly or indirectly, to or for the use or benefit of any official or employee of the government, political party, official, or candidate.

16.2 In addition, the Client shall act consistently with the Bureau Veritas' Code of Ethics.
https://group.bureauveritas.com/group/corporate-social-responsibility

GUIDANCE NOTE NI 638

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Section 4 Short-term and Long-term Variability

Section 5 Short-term Statistics

Appendix 3 Strategies for the Determination of Extreme Response / Fatigue Damage

SECTION 1 GENERAL

1 Introduction

1.1 Context

1.1.1 In the design process of ships and offshore units, long-term direct hydro structure analysis, as defined in [2.1], are widely used to assess the robustness of a given design regarding the possible failure modes. Several methods can be used to assess the extreme stress in the structural members or the fatigue damage, depending on the loads to be considered and the type of response to compute.

1.2 Application

1.2.1 This Guidance Note describes various methods and tools that can be used for the direct calculations of the hydro-structural response of ships and floating or fixed offshore units.

1.3 Scope

1.3.1 The main purpose of the present Guidance Note is to present several approaches to perform a long-term analysis and to provide the associated theoretical background. This Guidance Note mainly focus on the tools and background of the long-term analysis itself, however it also provides information on environmental conditions and hydro-structure models respectively in Sec 2 and Sec 3.

2 Long term analysis

2.1 Definition

2.1.1 A long-term analysis consists in simulating the ship or offshore unit behaviour over a very long period of time (several years), where the vessel will encounter many different environmental conditions. The objective of the long-term analysis is to compute:

- the extreme response over that period of time (extreme stress, motion or load)
- the accumulated fatigue damage over that period of time.

These results are obtained from the combination of the short-term results for the different environmental conditions. A secondary output of the long-term analysis is the list of the short-term conditions (heading, sea-state) having the highest contribution to the extreme response or to the fatigue damage.

2.2 General methodology

2.2.1 Input data and model

A complete description of the environmental conditions is needed to perform a long-term analysis. This description can come from hindcast data or from a scatter diagram (see Sec 2 and App 1).

To compute the hydro-structure unit response on every sea-state of the environmental conditions, the first step is to build a representative model of the unit (see Sec 3) and to define the expected operational profile (see Sec 2).

If directionality information is available for both the operational profile (heading) and the environmental conditions (wave direction), it should be combined in order to obtain a relative wave direction for each short-term condition.

Note 1: For turret moored offshore units, this relative wave direction can be the outcome of a heading analysis.

If either the vessel heading or the wave direction information is not available, a probability distribution of relative wave direction is to be set, thus increasing the number of short-term conditions to be considered. Equiprobability of the relative wave direction is considered in the absence of detailed information.

2.2.2 Characterization of the short term distributions

Short term statistics are used to characterize the short-term distribution of the response cycles. The knowledge of this distribution, or at least of the tail of the distribution, is necessary to perform the long-term analysis. The different approaches used to perform short-term statistics are presented in Sec 4 and Sec 6.

2.2.3 Characterization of long term distributions

Several methods can be employed to perform a long-term analysis. The most complex ones simulate all the life-time unit response, while the simplified methods, under given assumptions, focus on a limited number of simulation cases. All these methods are presented in Sec 6.

2.3 Different strategies for long-term analyses

2.3.1 A summary of the different strategies available to determine the long-term extreme response and damage is presented in App 3 with references to the different Sections of the Guidance Note for the detailed methods and definition.

SECTION 2 ENVIRONMENTAL AND OPERATING CONDITIONS

Symbols

H_S : Significant wave height, in m

T_p : Peak period, in s

T_Z : Zero up-crossing period, in s

β : Wave heading relative to the unit axis, in degree. For head seas: β = 180°, and β = 90° for waves coming from starboard

ω : Wave angular frequency, in rad/s

1 General

1.1 Purpose

1.1.1 The present Section defines environmental and operating conditions, considered as the input data for long-term analysis, i.e. the environmental conditions that the unit will encounter during its lifetime, including wave, wind, current as well as its operational profile.

1.2 Description of environmental conditions

1.2.1 Three main natural phenomena may contribute to structural damage or operation disturbances:

- current
- wind
- waves.

These phenomena are described by physical variables of statistical nature, both on the short and the long-term. Considering their potential effects on the design, there is a need for reliable data, representative for the area of operation and/or navigation, on a sufficiently long period.

1.2.2 If a reliable simultaneous database exists, the environmental phenomena can be described by joint probabilities. For vessels operating world-wide or in different zones, data from particularly hostile areas can be considered (North Atlantic for instance).

1.2.3 Reliable data defining correctly wave, wind and current and their joint probabilities for specific areas may be difficult to obtain. In the absence of multi-dimensional scatter diagrams, the long-term methodology described in this Guidance Note cannot be correctly developed. Considering that wave, wind and current are fully uncorrelated is a simplifying assumption that may be highly incorrect and could lead to unrealistic results. In the offshore industry, the environmental contours (see App 1) approach, with estimated associated value between the different parameters, are often used since the effect of wind and current cannot be neglected (in the evaluation of mooring line tensions for instance).

For ships, wind and current do not usually represent a relevant contribution to extreme stress or fatigue, hence only the wave (H_S, T_P and direction) are considered.

The main part of this Guidance Note focus on wave contribution.

1.3 Measurements

1.3.1 General

Different types of techniques exist in order to measure or generate the set of data required to describe the environment at a specific location. Some of these techniques are briefly presented hereafter.

1.3.2 Human observation at sea

As it is the simplest method to implement in order to derive wave data, this technique has been the earliest method used to build the first tabulation of wave height.

Thanks to the improvements made in measurements techniques, this method has been replaced by several more accurate techniques of measurement.

1.3.3 Buoy measurements

Moored buoys are frequently used to capture environmental data, as they are a practical solution capable of recording several type of information such as wind speed and direction, air and sea temperature, and wave energy spectra from which significant wave height, dominant wave period, and average wave period can be derived.

These type of buoys can be installed in both coastal and offshore waters. Generally using accelerometers, they capture the buoy motions and accelerations. Several methods of analysis are then available to derive the wave data.

1.3.4 Sensors on offshore structures

As per moored buoys, sensors can be installed on offshore structures in order to measure wind speed and direction, current speed, etc.

For wave measurements, several sensors may be used such as pressure gauge to derive wave height and period.

1.3.5 Satellite Altimeters

The satellite altimeters, that are used to measure surface geostrophic currents, also measure wave-height. Altimeter data are used to produce monthly mean maps of wave-heights and the variability of wave energy density over time and space.

1.3.6 Synthetic Aperture Radars on Satellites

Synthetic Aperture Radars (SAR) tend to map the radar reflectivity of the sea surface (spatial resolution from 6 to 25 meters). Depending on the conditions, synthetic aperture radars may lead to really good measure of the wave field, based on reflexivity analyses.

1.4 Hindcast data

1.4.1 According to the World Meteorological Organization (WMO), hindcasting refers to the diagnosis of wave information based on historical wind data. Hindcast wave data from numerical wave models are produced operationally and archived by many major meteorological services.

In other words, hindcasting techniques are used to provide statistical wave data over a large area in a short period of time. Wave data can be derived from wind field information using different methods, ranging from simple formulae to complex numerical models.

2 Waves

2.1 General description

2.1.1 In order to properly describe the sea-states that the ship or offshore unit will face over its lifetime, two descriptions are used:

- the short-term description
- the long-term description.

The short-term description, as defined in [2.2], is used to define one specific wave condition over a short duration (usually 3 hours) where the sea-state is considered as stationary.

The long-term description, as defined in [2.3], is used to define all the different wave conditions that can occur over a long period of time, usually several years, corresponding to the lifetime of the ships or offshore units.

2.2 Short-term wave conditions

2.2.1 Description

The description of short-term wave conditions may be given by:

- wave spectra, or
- wave statistics.

2.2.2 Wave spectrum

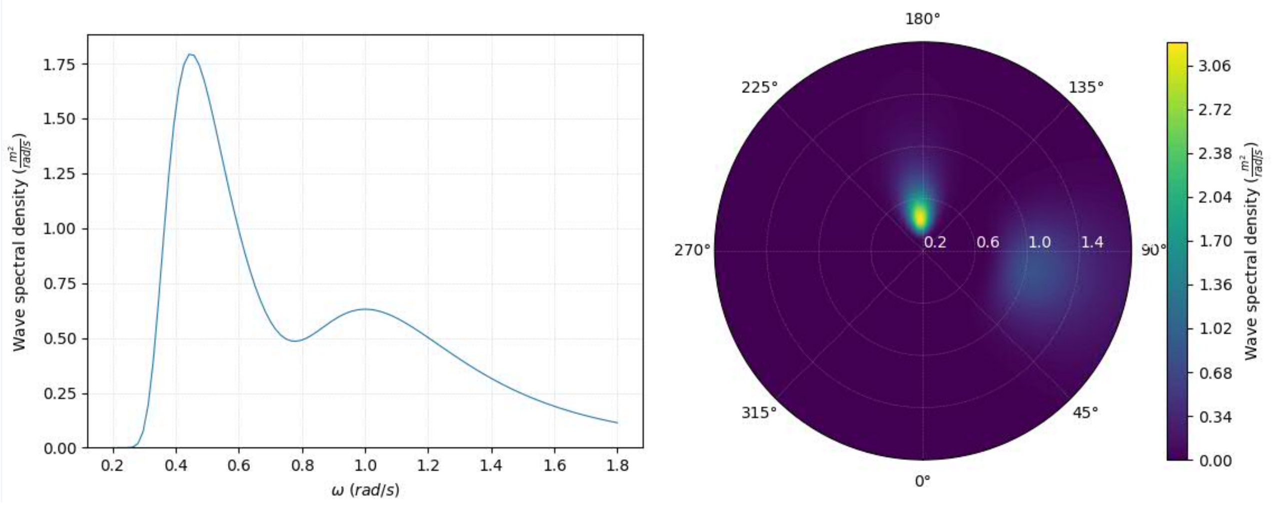
A short-term sea-state is described by a wave energy density spectrum, (see Fig 1) which is the power spectral density function of the vertical sea surface displacement. Wave spectra are often given in the form of an analytical formula.

Directional short-crested wave spectra $S_\eta(\omega, \beta)$ may be expressed in terms of a unidirectional wave energy density spectrum $S_\eta(\omega)$ multiplied by an angular spreading function $G(\beta)$:

$$S_\eta(\omega, \beta) = S_\eta(\omega) \cdot G(\beta)$$

For a two-peak spectrum expressed as a sum of a swell component and a wind-sea component, each component may have its own spreading function (see [2.2.7] and [2.2.8]). Different spectra can be found in the literature, such as Pierson-Moskowitz (see [2.2.4]), Jonswap (see [2.2.5]), Ochi-Hubble (see [2.2.6]), etc.

Figure 1 : Examples of wave spectral density



2.2.3 Spectral model

The spectral model are characterized by some of the following characteristics:

- spectrum moments

$$m_n = \int_0^{\infty}\int_0^{2\pi} \omega^n S(\omega) D(\omega, \beta) d\beta d\omega$$

- standard deviation

$$\sigma = \sqrt{m_0}$$

- significant height

$$H_S = 4\sqrt{m_0}$$

- mean up-crossing period

$$T_Z = 2\pi\sqrt{\frac{m_0}{m_2}}$$

- mean crest period

$$T_C = 2\pi\sqrt{\frac{m_2}{m_4}}$$

- bandwidth

$$\varepsilon = \sqrt{\left(1 - \frac{m_2^2}{m_0 m_4}\right)}$$

2.2.4 Pierson-Moskowitz spectrum

The Pierson-Moskowitz spectrum is frequently applied for wind seas. It was originally proposed for fully-developed seas. It describes the wind-sea conditions that often occur for the most severe sea-states. The Pierson-Moskowitz spectrum is given by:

$$S_\eta(\omega) = \frac{5\omega_p^{\ 4} H_S^{\ 2}}{16\omega^5} \cdot \exp\left[-1,25\left(\frac{\omega_p}{\omega}\right)^4\right]$$

where:

ω_p : Peak angular frequency.

$$\omega_p = \frac{2\pi}{T_p} = \frac{2\pi}{1,408 T_Z}$$

2.2.5 JONSWAP spectrum

The JONSWAP spectrum is formulated as a modification of the Pierson-Moskowitz spectrum for a developing sea-state in a fetch limited situation. It includes a peak-enhancement factor, the effect of which is to increase the peak of the Pierson-Moskovitz spectrum. The JONSWAP spectrum is given by:

$$S_\eta(\omega) = A \cdot \frac{5\omega_p{}^4 H_S{}^2}{16\omega^5} \cdot \exp\left[-1,25\left(\frac{\omega_p}{\omega}\right)^4\right] \cdot \gamma^{\left[\exp\left(\frac{-(\omega-\omega_p)^2}{2\sigma^2\omega_p{}^2}\right)\right]}$$

where:

γ : Peak enhancement factor. For $\gamma = 1$ the JONSWAP spectrum corresponds to a Pierson-Moskowitz spectrum

σ : Relative measure of the peak width. In the most cases:

- for $\omega < \omega_p$: $\sigma = 0{,}07$
- for $\omega > \omega_p$: $\sigma = 0{,}09$

$$A = \frac{1}{5(0,065\gamma^{0,803} + 0,135)}$$

2.2.6 Ochi-Hubble spectrum

Combined wind-sea and swell may be described by a double peak frequency spectrum, i.e. where wind-sea and swell are assumed to be uncorrelated. The Ochi-Hubble spectrum is a general spectrum formulated to describe bimodal sea-states.

The spectrum is a sum of two gamma distributions, each with 3 parameters for each wave system:

$$S_\eta(\omega) = \frac{1}{4}\sum_{i=1}^{2}\left\{\left[\omega_{p,i}^4\left(\lambda_i + \frac{1}{4}\right)\right]^{\lambda_i} \cdot \frac{H_{s,i}^2}{\Gamma(\lambda_i)\omega^{4\lambda_i+1}} \cdot \exp\left[-\left(\lambda_i + \frac{1}{4}\right)\left(\frac{\omega_{p,i}}{\omega}\right)^4\right]\right\}$$

where:

$\omega_{p,i}$: Peak angular frequency, in rad/s, of component i

$H_{S,i}$: Significant wave height, in m, of component i

λ_i : Spectral shape parameter of component i.

2.2.7 Spreading function with ‘cos n’ formulation

The most commonly used directional spreading function is:

- when $|\beta - \beta_0| \le 90°$:

$$G(\beta) = \frac{\pi}{180} \cdot \frac{\Gamma(n/2+1)}{\sqrt{\pi}\,\Gamma(n/2+1/2)} \cdot \cos^n(\beta - \beta_0)$$

- when $|\beta - \beta_0| > 90°$:

$G(\beta) = 0$

where:

β_0 : Main wave heading relative to the ship bow, in deg

n : Spreading parameter specified according to the metocean data.

2.2.8 Spreading function with ‘cos 2s’ formulation

An alternative formulation for the directional spreading function is:

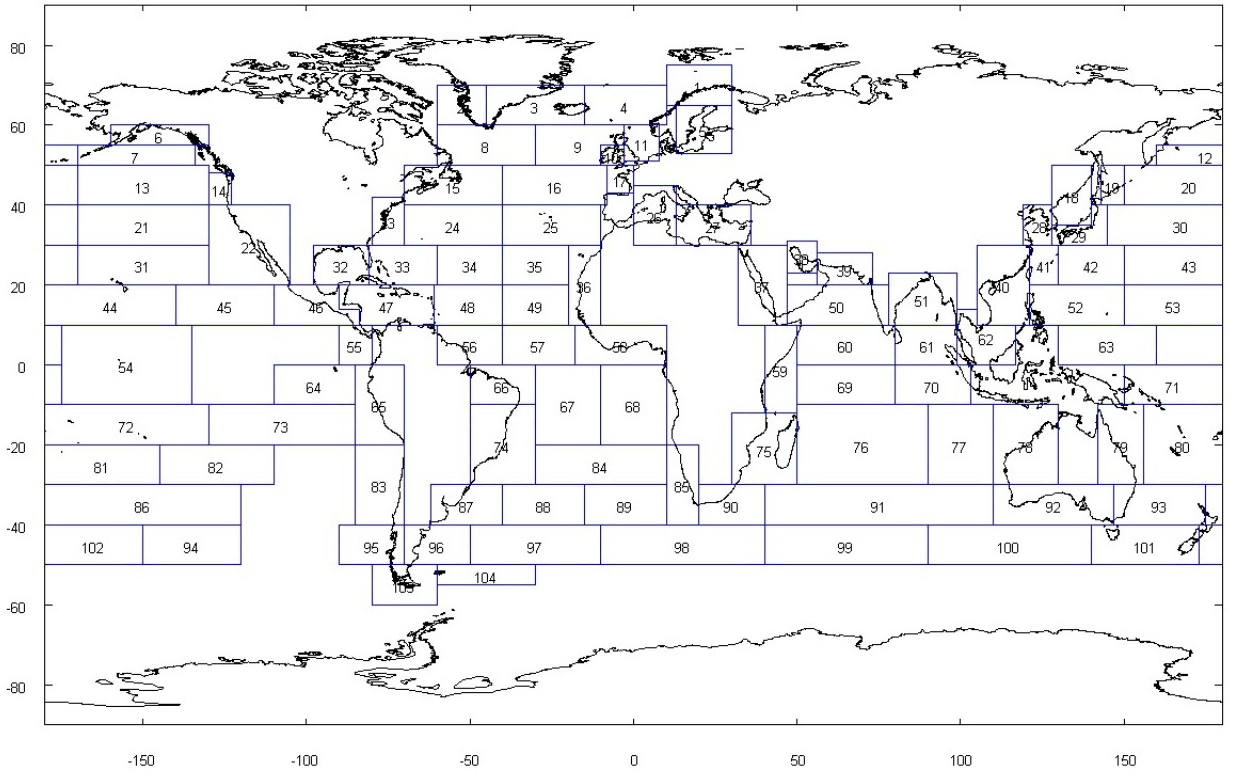
$$G(\beta) = \frac{\pi}{180} \cdot \frac{\Gamma(s+1)}{2\sqrt{\pi}\,\Gamma(s+1/2)} \cdot \cos^{2s}\left(\frac{\beta - \beta_0}{2}\right)$$

where:

β_0 : Main wave heading relative to the ship bow, in deg

s : Spreading parameter specified according to the metocean data.

Figure 2 : Areas of the global wave statistics



2.3 Long term wave conditions

2.3.1 Description

The description of long-term wave conditions may be given by:

- scatter diagrams (see [2.3.2], [2.3.3] and [2.3.4])
- list of sea-states (see [2.3.5])
- envelope sea-states (see [2.3.6]).

2.3.2 Wave scatter diagram

A wave scatter diagram is a description of the joint probabilities of wave heights and wave periods. This description is made for a given geographical area. The scatter diagrams are usually based on visual observations and hindcast data, which are merged and extrapolated, using some analytical functions. The global wave statistics atlas provides scatter diagrams for 104 areas in the world, including some seasonal and directional information (see Fig 2). The scatter diagrams generally used for the design of ships without any specific sailing area are those provided in [2.3.3] and [2.3.4].

It is important to note that field measurements lead to scattered data from limited duration. They usually cannot be used for extreme calculations.

2.3.3 IACS scatter diagram

The IACS scatter diagram has been defined from the winter data of areas 8, 9, 15 and 16 (North Atlantic). This scatter diagram is the basis of many standard long-term analyses since the North Atlantic is considered as the most severe area in the World (considering the wave heights).

The IACS scatter is defined according to the following probability density function:

$$P_{IACS}(H_S,T_Z) = \frac{\beta}{\alpha}\left(\frac{H_S-\gamma}{\alpha}\right)^{\beta-1}\exp\left[-\left(\frac{H_S-\gamma}{\alpha}\right)^{\beta}\right]\frac{1}{T_Z\sigma\sqrt{2\pi}}\exp\left(-\frac{(\ln(T_Z-\mu))^2}{2\sigma^2}\right)$$

where:

$\alpha = 3{,}041$

$\beta = 1{,}484$

$\gamma = 0{,}66$

$\mu = 0,7 + 1,27\, H_S^{0,131}$

$\sigma = 0,1334 + 0,0264 \exp(-0,1906\, H_S)$

The sea-states are to be modeled by a Pierson-Moskowitz spectrum and a 'cos n' spreading function with n = 2, as defined in [2.2.4] and [2.2.8]. Equiprobability of the main wave direction is to be considered.

2.3.4 Worldwide scatter diagram

The worldwide scatter diagram is representative of wave conditions for worldwide trips is defined according to the following probability density function:

$$P_{WW}(H_S,T_Z) = \frac{\beta}{\alpha}\left(\frac{H_S-\gamma}{\alpha}\right)^{\beta-1}\exp\left[-\left(\frac{H_S-\gamma}{\alpha}\right)^{\beta}\right]\frac{1}{T_Z\sigma\sqrt{2\pi}}\exp\left(-\frac{(\ln(T_Z-\mu))^2}{2\sigma^2}\right)$$

where:

$\alpha = 1,807$

$\beta = 1,217$

$\gamma = 0,83$

$\mu = -0,1 + 2,847\, H_S^{0,075}$

$\sigma = 0,161 + 0,146 \exp(-0,683\, H_S)$

The sea-states are to be modeled by a Pierson-Moskowitz spectrum and a 'cos n' spreading function with n = 2, as defined in [2.2.4] and [2.2.8]. Equiprobability of the main wave direction is to be considered.

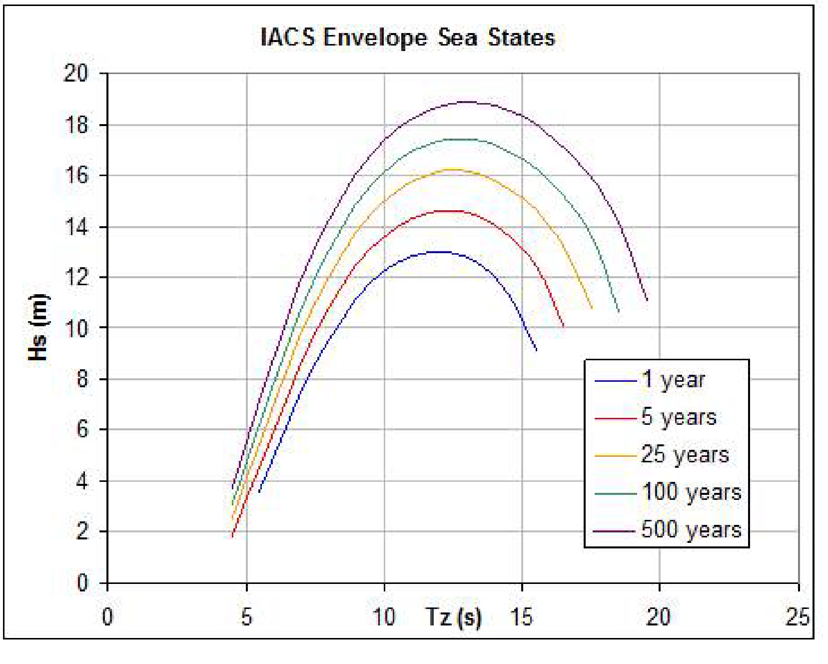
2.3.5 List of sea-states

Lists of sea-states may be used as input data for certain analyses. They are based on hindcast or measured data at specific location and give a precise description of the short-term spectrum. The list may contain information on current, wind and multiple wave systems, each with their own properties like direction and magnitude.

2.3.6 Envelope sea-states

The envelopes sea-states are based on the Inverse First Order Reliability Method (I-FORM), as detailed in App 1, [2.2.1]. They are derived from the analytical formulation of the scatter diagram and are defined by a short-term duration (usually 3 hours) and a given long-term return period (see Fig 3).

Figure 3 : IACS envelope sea-states



3 Operating conditions

3.1 Vessel operational profile

3.1.1 Loading conditions

The definition of the loading conditions allows to calculate hydrostatic data such as draft, trim, displacement, position of the center of gravity, GM value, etc.

In order to perform extreme or fatigue calculations, it is necessary to correctly define the loading conditions and the percentage of time that the vessel intends to be loaded in each condition.

As an example, the following loading conditions are usually defined: full load, alternate, normal ballast, heavy ballast in either transit, site or hull damaged conditions (non exhaustive list).

3.1.2 Ship speed and heading

The ship speed and heading generally depend on the sea-states encountered by the ship.

Involuntary speed reduction may occur due to several factors such as added resistance or wind resistance.

Voluntary speed reduction may be a consequence of captain decision in order to avoid damaging the ship or the cargo (severe slamming, extreme motions, propeller emergence).

3.1.3 Wave relative heading

The wave relative heading is a key point when performing calculations to assess the design of the vessel. This wave relative heading is driven by two parameters:

- vessel direction
- wave direction.

Particular attention is to be paid for the signs and referential system used for both the vessel and the wave directions.

3.1.4 Rules

Usually, class rules give specific recommendations to account for the speed for extreme and fatigue calculations.

SECTION 3 HYDRO-STRUCTURE CALCULATIONS

1 General

1.1 Objective

1.1.1 The objective of hydro-structure calculations is to compute the behaviour of the ship/offshore unit when facing a given environmental condition.

Different outputs can be computed through hydro-structure calculations such as:

- motions and accelerations
- pressures on the hull and inside the tanks
- hull girder loads.

1.2 Evaluation of the response

1.2.1 A good evaluation of the structural response of a ship in waves needs a proper coupling between a hydrodynamic model, which describes the hydrodynamic interaction between the ship and the waves, and a structural model, which describes the structural response to the wave induced loads. Several levels of assumptions can be chosen for the hydrodynamic model and the structural model, depending on which physical behaviour is expected to be reproduced.

From the hydrodynamic analysis point of view, see [2.1], the loads can be considered as:

- linear (valid only for the smallest sea-states), as described in [2.1.1]
- weakly non-linear (e.g. Froude-Krylov loads as described in [2.1.2], or Morison loads as described in [2.1.3])
- highly non-linear or impulsive (e.g. slamming loads, as described in [2.1.4]).

From the structural analysis point of view, see [3], the response can be considered as:

- quasi-static, which means that the structural response is strictly proportional to the applied loads. This model is described in [3.1]
- dynamic, if a dynamic amplification or a resonant response occurs. This model is described in [3.2]
- non-linear (e.g. large deformation, contact, friction).

2 Loads

2.1 Hydrodynamic loads

2.1.1 Linear loads

The linear part of the hydrodynamic loading is calculated by a validated numerical sea-keeping code. The use of codes based on the Boundary Element Method (BEM) is recommended. In the case of linear calculations, the mesh contains the mean underwater part only. The mesh size is to be chosen so that the minimal wave length (defined on the basis of encounter frequency) is covered by at least eight panels. Alternatively, a special treatment of the high frequency calculations can be used in order to avoid the numerical inaccuracies inherent to the BEM method. In any case, the problem of irregular frequencies is to be properly solved.

2.1.2 Froude-Krylov non-linear loads

When non-linear hydrodynamic simulations are performed, the minimum non-linear loads that should be included are based on the so called Froude-Krylov approximation. The pressure of the undisturbed incoming wave is applied to the hull on every wet panel, and not only under the mean waterline as it is the case in the linear computation. The non-linear hydrostatic restoring forces are also included by taking into account the real position of the ship in the integration of the hydrostatic pressure. The mesh used to integrate the pressure loading is to include the part of the hull above the mean waterline.

2.1.3 Morison non-linear loads on slender elements

The Morison loads on slender structural elements, mainly of offshore units, can be introduced in non-linear hydrodynamic simulations. The general expression for these loads is:

$$dF_M = \frac{1}{2}\rho C_D D\left(\nu - \frac{dx}{dt}\right)\left|\nu - \frac{dx}{dt}\right| dl + \rho\frac{\pi D^2}{4}\left[(1 + C_M)\frac{d\nu}{dt} - C_M\frac{d^2x}{dt^2}\right]dl$$

where:

ρ : Fluid density, in kg/m³

D : Diameter of the slender element, in m

C_D, C_M : Drag and added mass coefficients, respectively

ν, $d\nu/d\tau$: Local fluid velocity and acceleration, respectively in m/s and m/s², perpendicular to the slender element axis

dx/dt, d^2x/dt^2 : Local velocity and acceleration, respectively in m/s and m/s², of the slender element due to the units motions.

2.1.4 Slamming

For ships (e.g. bow slamming on container ships), if slamming loads are considered in the simulation, the slamming pressures are to be computed using either a Computational Fluid Dynamic (CFD) code or a BEM code, provided that these codes are properly validated and coupled with the sea-keeping code. The slamming pressures are to be properly transferred to the Finite Element (FE) model at each time step of the time domain simulation.

2.2 Internal liquid loads

2.2.1 General

Different assumptions can be used for taking the liquids in tanks into account on the structural model (see Tab 1). The validity of the different models depends on the following criteria:

a) the pressure exerted by the liquid in the tank has no direct influence on the response of the considered structure

b) the liquid in the tank have a significant hydrostatic effect (significant free surface effect impacting the unit motions at sea)

c) the liquid in the tank have a significant hydrodynamic behaviour (sloshing in the sense of dynamic liquid motions, not covering impacts).

The risk of dynamic fluid behaviour depends on the dimensions of the tank and on the presence of structural elements inside the tank capable of preventing or strongly damping such motions (e.g. in a double hull of double bottom tank).

In any case, the choice of a model for the liquid in tank is to be carefully reflected in the structural model as well as in the hydrodynamic model, in order to keep the consistency between the two models for the sake of the structural model balance in the hydro-structure coupling procedure.

2.2.2 Tank mass

If the liquid in tank fulfils the criteria a) and b) of [2.2.1], then it can be simply represented as a mass matrix.

On a FEM model, the mass matrix element is to be attached to the tank boundaries by means of special elements which do not introduce any rigidity in the model (interpolation elements). Modelling the mass of the liquid with lumped masses directly located on the tank boundaries is not recommended as it creates some overestimated mass moments of inertia with very limited options to adjust them.

The mass, centre of gravity and mass moments of inertia resulting from the modelling of the liquid as a mass in the structural model are to be used in the hydrodynamic model.

Table 1 : Models for liquids in tanks

	Mass matrix	
Mass model	Linear model	Non-linear Model
Hydrostatic model	simplified pressure model (see [2.2.3]	simplified pressure model (see [2.2.3], valid only for p_{liq}>0)
Hydrodynamic model	linear hydrodynamic computations	CFD computations

2.2.3 Simplified pressure model

A simplified pressure model can be used when the liquid in tank fulfills the criterion c) of [2.2.1]. In this case, the effect of the fluid is modeled as a pressure defined with the following analytical formulae:

- if $z \le z_F$ $p_{liq} = \rho\,[(x - x_F)\,\gamma_x + (y - y_F)\,\gamma_y + (z - z_F)\,\gamma_z]$
- if $z > z_F$ $p_{liq} = 0$

where:

(x, y, z) : Location where the pressure is evaluated, in m

(x_F, y_F, z_F): Location of the centre of the tank liquid free surface, in m

ρ : Liquid density, in kg/m^3

$(\gamma_x, \gamma_y, \gamma_z)$: Local acceleration at the tank centre of gravity, in $m{\cdot}s^{-2}$.

The acceleration at the tank centre of gravity is deduced from the ship accelerations at the motion reference point, using the rigid body kinematic rule. The ship accelerations include the terms due to the influence of gravity when the unit pitches and rolls.

In case of a fully filled tank, the same pressure formulation can be used, setting the 'centre of liquid free surface' at the uppermost point of the tank, or at the centre of the liquid free surface for a 'almost fully filled tank'. However, z_F is to be chosen so that $z_F \ge z$ whatever z, in order that no free surface effect occurs.

The tank is to be introduced in the hydrodynamic model in a way fully consistent with the loads exerted on the structural model according to the above formulae. To this effect, the terms of the tank hydrostatic restoring matrix and mass matrix can be determined considering unitary motions, determining the liquid pressure resulting from the above formulae and integrating this pressure on the tank boundary.

2.2.4 Hydrodynamic tank pressure

If a significant fluid dynamic behaviour is expected, then the pressure exerted by the liquid is to be determined by means of a hydrodynamic computation and transferred to the structural model. As a general rule, the hydrodynamic model used for the external problem related to sea pressure is also to be used for solving the tank hydrodynamic problem.

3 Structural ship/offshore unit response

3.1 Quasi-static response

3.1.1 Once the hydrodynamic sea-keeping problem is solved, the different loading cases for FE model analysis need to be constructed.

Each loading case is composed of the hydrodynamic pressure loading on the wet panels, the inertial and the gravity loading on each finite element and the additional damping loading. The perfect equilibrium of the overall loading needs to be ensured. In general, the hydrodynamic and structural meshes are different, and special care is to be given to the pressure transfer.

The structural problem is solved using FEA software for each loading case. The structural response is supposed to be static and linear. In order to ensure equilibrium of the coupled model, the mass distribution of the FEA model shall be equivalent to the mass distribution used for the hydrodynamic analysis. Adjustment of material density in FE model may be found necessary in order to match with lightship condition of the unit.

3.2 Dynamic response

3.2.1 If a dynamic ship response is anticipated, a coupled hydro-elastic model should be used.

The first step of the dynamic analysis is the modal FEM model analysis in dry condition (i.e. without liquid added mass effect), which is to be done with care. Local structural modes are to be removed. The first ten dry eigen modes are normally considered to be sufficient.

Once the dry modes are obtained, the modal displacements are to be transferred from the structural model to the hydrodynamic model and the corresponding hydrodynamic problems are to be defined. Once the hydrodynamic problems are solved, a fully coupled dynamic equation is solved, giving both the rigid body motions and the structural response in terms of modal amplitudes.

The modal reduction of the structural response is usually not fully satisfactory for strength or fatigue verification, since the number of modes in the base is not sufficient to capture the full distortion of the structure, in particular regarding the quasi-static response of the transverse structure. Therefore, the structural response needs to be evaluated by a quasi-static approach, in which the pressure and inertia loads arising from the hydro-elastic dynamic equation are applied in a static way on the FEM model. Alternatively, the motion equation results can be separated into a quasi-static part and a dynamic part. The quasi-static part of the response is then calculated using the quasi-static method while the dynamic part of the response is calculated by summing up the dynamic contribution of each mode.

4 Models

4.1 Hydrodynamic models

4.1.1 Linear model in frequency domain

This type of models are the most commonly used to compute the ship response to waves. Diffraction radiation codes based on potential theory allow to build linear models in frequency domain.

This model is only valid for low and medium sea-states, since it does not account for the non-linear effect that can occur in higher waves.

4.1.2 Non-linear hydrodynamic model in time domain

This more complex model can be used for all sea-states since it is able to account for response non-linearities (Froude Krylov) or slamming impulsive loads.

The drawback of this model is that it can quickly become time consuming or even very time consuming depending on the assumptions that are made.

4.1.3 Model tests and full scale measurement

These models can be really accurate since they can give a better representation of the reality, even though they may be really difficult to tune and interpret properly (scale effects, tuning of all mass components, noise, etc.)

Model tests can be conducted with a strict control of the operating conditions (sea-state, heading, etc.). However, they are often really expensive and only a limited number of conditions can be studied.

Full scale measurement try to capture the ship real behaviour, so the accuracy can be better than any numerical simulations. The drawbacks are the complexity of such system, the need to couple ship and sea-state measurement systems, and the fact that external conditions cannot be controlled and imposed.

4.2 Structural models

4.2.1 2D models

2D models may include plates and stiffeners contributing to hull girder strength. They are used to combine local strength and hull girder strength for linear and non-linear behaviour.

2D models are the simplest models, they allow fast and efficient calculations.

4.2.2 3D Finite Element Method (FEM) models

3D FEM models allow to take into account local details, such as primary supporting members. Various element types and sizes can be considered to refine the model.

3D FEM models are used to simulate structural behaviour.

Two types of FEM model can be distinguished:

- global models
- local models.

4.2.3 Global models

These models combine primary supporting members (PSM) and plate and stiffeners contribution to hull girder strength.

Full length models or large partial models can be used considering coarse mesh or relatively fine mesh.

4.2.4 Local models

Local models may be used to study local strength and local stress concentration. Deformation of PSM and hull girder behaviour are obtained from global model (see [4.2.3]).

For this type of model, fine meshes or very fine meshes have to be used.

4.3 Hydro-structure models

4.3.1 General

The hydrodynamic model and the structural model need to be combined in order to determine the structural response to the environment.

According to the selected structural model (2D analytical model or 3D-FEM model), the loads to be transferred are defined (internal loads, accelerations, pressures).

It is also to be noted that partial 3D models can also be used for specific applications.

4.3.2 Coupled hydro-elastic models

For some specific applications, the structural response of the ship and the hydrodynamic analysis cannot be separated, so a coupled hydro-elastic model is necessary.

5 Types of hydro-structure simulations

5.1 General

5.1.1 Different parameters define the type of simulation to be used:

- type of analysis (global or local)
- waves (regular or irregular)
- required outputs (motions, internal loads, stress)
- loads (linear, weakly non-linear or non-linear)
- type of resolution (time domain or frequency domain)
- structural response (quasi-static or dynamic).

By combining these different parameters, considering the physical phenomenon to be studied, we can define the most efficient and accurate analysis to be performed. In this Article, the main types of simulations are presented.

5.2 Linear loads and quasi-static structural response solved in frequency domain

5.2.1 Description

In this analysis we are considering a quasi-static structural response with linear wave loads, and we use a frequency domain resolution. The ship is considered as a rigid body with 6 degrees of freedom. The linear potential flow model is used to solve the hydrodynamics in the frequency domain. Then the structural response is solved in quasi-static after pressure transfer.

It is important to note here that hydrodynamic and structural calculations can be performed separately. Dynamic effect and non-linearities cannot be taken into account using this approach, but the computing time is relatively low.

5.2.2 Typical application: linear sea-keeping

Rigid body linear sea-keeping response can be simulated using the quasi-static structural model (see [3.1]) with linear hydrodynamic loads (see [2.1.1]). This model is a frequency domain model (see [4.1.1] and is used for linear spectral fatigue assessment without springing effects.

5.3 Linear loads and dynamic structural response solved in frequency domain

5.3.1 Description

For this analysis we are considering a dynamic structural response with linear wave loads, and we use a frequency domain resolution.

As per [5.2.1], hydrodynamic and structural calculations can be computed separately. Non-linearities cannot be considered due to the frequency domain resolution. The ship is considered as a rigid body with 6 degrees of freedom.

5.3.2 Typical application: linear springing

A typical application of this approach is the computation of linear springing. The springing is defined as the resonant hull girder vibrations due to oscillating wave loads along the hull.

Linear springing response can be simulated using the dynamic structural model (see [3.2]) with linear sea-keeping loads (see [2.1.1]). This model is a frequency domain model (see [4.1.1]) and is used for linear fatigue assessment including springing effects.

5.4 Weakly non-linear loads, quasi-static and dynamic responses solved in time domain

5.4.1 Description

To account for non-linear loads, it is necessary to work in time domain (it is possible to perform some non-linear simulations in frequency domain using the higher order theories but these methods are not employed very often because of the complexities associated with the solution).

The structure response can be both computed as dynamic or quasi-static. In this approach, hydrodynamic and structure calculations are coupled.

Typical applications of this approach are non-linear sea-keeping and non-linear springing.

5.4.2 Typical application for quasi-static response: non-linear sea-keeping

Non-linear hull girder loads, such as hogging and sagging bending moments, or non-linearities of sea level pressure, can be evaluated using Froude-Krylov non-linear wave loads (see [2.1.2]) with a quasi-static structural response (see [3.1]). This model is a time-domain model (see [4.1.2]) and can be used for ultimate strength assessment.

5.4.3 Typical application for dynamic response: non-linear springing

As this model is taking into account non-linear wave loads and a structural dynamic response, it can simulate linear and non-linear springing. Non-linear wave loads (see [2.1.2]) are combined with a dynamic ship response model (see [3.2]). This model is a time-domain model (see [4.1.2]).

5.5 Highly non-linear loads, quasi-static and dynamic responses solved in time domain

5.5.1 Description

In this approach, non-linear loads (for instance impact loads, such as slamming loads) are computed in time domain in order to capture highly non-linear effect. The response of the structure can also be both quasi-static or dynamic, depending on the requested outputs.

Typical applications of this approach are the computation of local response (quasi-static response) or whipping (dynamic hull girder response). The whipping is defined as the transient hydro-elastic ship structural response due to impulsive loading such as slamming, green water, underwater explosion, etc.

5.5.2 Typical application for quasi-static response: local slamming

Local structural deformations due to slamming pressures can be computed using impulsive slamming hydrodynamic loads (see [2.1.4]) with a local quasi-static structural model (see [3.1]).

5.5.3 Typical application for dynamic response: non-linear springing and slamming induced whipping

This model is the most complex as it includes Froude-Krylov non-linear loads (see [2.1.2]) and slamming loads (see [2.1.4]), coupled with a structural dynamic response (see [3.2]). This model is a time-domain model (see [4.1.2]). It can simulate linear and non-linear springing as well as slamming-induced whipping. It is to be noted that it is not possible to separate the whipping response from the springing response. This model is used for ultimate strength assessment and non-linear fatigue assessment.

5.6 Summary

5.6.1 The different types of approaches are summarized in Tab 2, with their typical applications. The CPU time increase from the left upper part (quasi-static and linear) to the right lower part (dynamic and non-linear).

Again, the choice of frequency or time domain resolution is linked to the need to account for non-linearities in the loads and outputs.

Table 2 : Different types of approaches depending and their applications

Structure response	Hydrodynamic loads		
	Linear	Weakly non-linear	Highly non-linear
Quasi-static	linear sea-keeping (see [5.2])	non-linear sea-keeping (see [5.4])	local slamming response (see [5.5])
Dynamic	linear springing (see [5.3])	non-linear springing (see [5.4])	whipping (see [5.5])

SECTION 4 SHORT-TERM AND LONG-TERM VARIABILITY

1 General

1.1 Objective

1.1.1 The objective of this Section if to define both short-term and long-term variabilities, and the associated short-term and long-term distributions. Statistical tools and definitions, including background of spectral analysis, are also given in the following Articles.

2 Short-term variability

2.1 Definition

2.1.1 In the design process of marine and offshore systems, the long-term evolution of ocean waves (and wind) is usually modeled as a succession of 3 hours stationary states. These limited periods of time can be considered as the short-term descriptions of the environment. Based on this assumption of stationarity for a short period, a sea-state can be characterized by some specific parameters (significant height and peak period for waves, mean speed for wind). Moreover, the concept of spectral density can be used for the simulation of waves and wind process. Various spectra exist and their applications depend on the location area of the study. The spectrum gives the magnitude of energy and its frequency content

For time domain simulation, the spectrum is discretized in different frequency components. A summation of harmonic functions with random phase allows the simulation of wave elevation or wind speed. In numerical applications, the Monte Carlo method can be used to simulate the random selection required for time domain calculations. This randomness induces the short-term variability of the sea-state in the design process, and the variability of the short-term responses.

2.2 Short-term distribution of events

2.2.1 Definitions

For a short-term distribution of events (wave height, loads, stress cycles, etc.), the following characteristic values and functions are defined:

- the up-crossing period Tz
- the probability density function

$$f(x) = \frac{1}{\delta x} P(x \le X \le x + \delta x)$$

- the cumulative distribution function

$$P(x) = P(X \le x) = \int_0^x f(t)dt$$

- the exceedance rate

$$\nu(x) = \frac{1}{Tz}(1 - P(x))$$

with

$$\nu(0) = \frac{1}{Tz}$$

2.2.2 Use of short-term distribution in the computation of fatigue damage

For fatigue damage computation, the entire stress cycles distribution $f(\Delta\sigma)$ is needed.

$$f(\Delta\sigma) = -Tz\frac{d\nu(\Delta\sigma)}{d\Delta\sigma}$$

The fatigue damage is computed using Palmgreen-Miner assumption and the mean period Tz:

- S-N curve gives the number of cycles to rupture:

  $$N(\Delta\sigma) = K \cdot \Delta\sigma^{-M}$$

  with K being the characteristic constant of the S-N curve, and M being the characteristic inverse slope of the S-N curve.

- the damage rate (per unit time) D_t^{ST} is given by:

  $$D_t^{ST} = \frac{1}{Tz}\int_0^{\infty}\frac{f(\Delta\sigma)}{N(\Delta\sigma)}d\Delta\sigma = \int_0^{\infty}\frac{d\nu(\Delta\sigma)}{d\Delta\sigma}\frac{1}{N(\Delta\sigma)}d\Delta\sigma$$

- short-term damage over a duration T:

  $$D_T = T \times D_t^{ST}$$

2.3 Maximum response over a duration T

2.3.1 If the number of N independent events is defined as N=T/Tz:

- the cumulative distribution function of the maximum response over a duration T is given by:

  $$P_{MAX}(x, T) = P(x)^{T/T_Z} = \left(1 - \frac{\nu(x)}{\nu(0)}\right)^N$$

- the distribution function is given by:

  $$f_{MAX}(x, T) = \frac{dP_{MAX}}{dx} = \left(\frac{T}{Tz}\right)f(x)P(x)^{\frac{T}{T_z}-1}$$

- the value exceeded with a risk α is defined as:

  $$P_{MAX}(x, T) = 1 - \alpha \Leftrightarrow P(x) = (1 - \alpha)^{\frac{1}{N}}$$

- the quantile 1/e of the max response over a duration T is defined as being the return value corresponding to a return period equal to T, hence:

  $$P_{MAX}(x_T, T) = \frac{1}{e}$$

- the most probable maximum is defined as the value of the maximum of a variable with the highest probability of occurring over a defined period of time T, hence the value for which f_{max} (x,N) is maximum

- the mean maximum is defined as:

  $$X = \int_0^{\infty} x f_{MAX}(x, N)dx$$

- from the definition of the return value x_T above, it can be written:

  $$P(x_T)^{T/T_Z} = e^{-1} \Leftrightarrow P(x_T) = e^{-T_z/T}$$

  for a T >> Tz:

  $$P(x_T) \approx 1 - \frac{T_Z}{T}$$

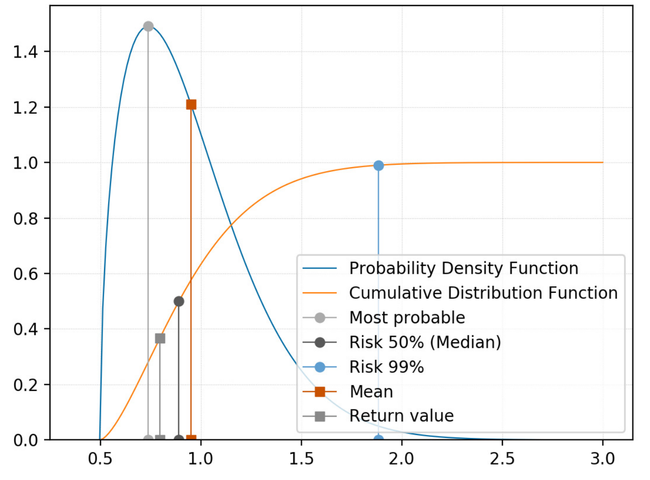
- the probability to exceed a return value x_{RP} (corresponding to return period RP) over a duration T is defined by:

  $$P_{MAX}(x_{RP}, T) = P(x_{RP})^{T/T_Z} = e^{(-T)/(RP)}$$

  for T<<RP:

  $$P_{MAX}(x_{RP}, T) = 1 - \frac{T}{RP}$$

Figure 1 : Characteristic values (for a 3 parameters Weibull distribution)



3 Response spectrum

3.1 General

3.1.1 In this Article, we consider that the transfer between the loads and the response can be taken as linear and time-invariant.

The spectral density of response $S_R(\omega)$ can be defined from the spectral density $S_w(\omega,\mu)$ (here representing the distribution in frequency (ω) and direction μ) of the wave energy and the RAO(ω,μ) as being the transfer function of any first order quantity, like motions, accelerations, relative wave elevation, stress, etc.

3.2 Spectral analysis

3.2.1 We consider the spectral density $S_w(\omega,\mu)$ representing the distribution in frequency (ω) of the wave energy and the RAO(ω,μ) as being the transfer function of any first order quantity, like motions, accelerations, relative wave elevation, stress, etc.

The spectral density of response $S_R(\omega)$ can be then defined as:

$$S_R(\omega) = RAO^2(\omega, \mu) \times S_w(\omega, \mu)$$

The spectral moments can be defined as:

$$m_n = \int_0^{\infty}\left(\int_0^{360} \omega_e^n RAO^2(\omega, \mu) S(\omega, \mu)\right)(d\mu) d\omega$$

with:

$$\omega_e = \omega - \frac{U\omega^2}{g}\cos\mu$$

where U is the vessel speed.

3.2.2 Some statistical parameters can then be obtained using spectral moments:

- the mean period T_m, often referred as T_1, is defined as:

$$T_m = 2\pi\frac{m_0}{m_1}$$

- the mean zero up-crossing period is defined as:

$$T_Z = 2\pi\sqrt{\frac{m_0}{m_2}} = T_2$$

- the mean period of maxima is defined as:

$$T_{MAX} = 2\pi\sqrt{\frac{m_2}{m_4}}$$

- the bandwidth of the response can be characterized by:

$$\varepsilon^2 = 1 - \frac{m_2^2}{m_0 m_4} = 1 - \left(\frac{T_{MAX}}{T_z}\right)^2$$

if $\varepsilon = 0$, the spectrum is defined as narrow banded

if $\varepsilon = 1$, the spectrum is defined as wide banded.

4 Long term variability

4.1 Definition

4.1.1 As it is explained in Sec 2, [2.3.1] the long-term description is used to define all the different wave conditions that can occur over a long period of time. The variability of the characteristic parameters (typically H_S and T_P) on a given location over a given period creates the long-term variability of the response.

4.2 Long-term distribution of events

4.2.1 Definitions

The long-term distribution of events (wave height, loads or stress cycles...) can be built from the convolution of short-term probabilities $P_i(x)$, as defined in [2.2], and long-term probabilities pss_i, defined as the joint probabilities in Sec 2. The long-term probabilities pss_i are given by scatter diagrams (see Sec 2, [2.3]).

The exceedance rate is analytically defined as:

$$\nu_{LT}(x) = T\sum_{i=1}^{N} \frac{pss_i}{Tz_i}(1 - P_i(x)) = T\sum_{i=1}^{N} pss_i n_i(x)$$

In a period T, the number of events is given by:

$$N_T = T \times \nu_{LT}(0) = T\sum_{i=1}^{N} \frac{pss_i}{Tz_i}$$

The mean period Tz is given by:

$$\overline{Tz} = \frac{T}{N_T} = \frac{1}{\sum_{i=1}^{N} \frac{pss_i}{Tz_i}}$$

For events occurring at wave frequency, the mean period Tz is around 8s and the number of cycles in 25 years is about 10^8.

Finally, the long-term probability distribution $P_{LT}(x)$ is defined as:

$$P_{LT}(x) = 1 - \overline{Tz} \times \nu_{LT}(x)$$

4.2.2 Use of long-term distribution in the computation of fatigue damage

Two different methods can be used to compute the long-term fatigue damage rate D_t^{LT} :

- the first approach consist in summing the damage over all the sea-states:

$$D_t^{LT} = \sum_{i=1}^{N} pss_i D_{t,i}^{ST}$$

- the second approach consists in computing the damage rate directly from the long-term distribution:

$$D_t^{LT} = T\int_0^{\infty} \frac{(d\nu_{LT}(\Delta\sigma))}{d\Delta\sigma} \frac{1}{N(\Delta\sigma)}(d\Delta\sigma)$$

The long-term damage D^{LT} over a life time T_{LT} is given by:

$$D^{LT} = T_{LT} \times D_t^{LT}$$

4.2.3 Contribution of sea-states

As per extreme calculations, it is possible to evaluate the contribution of each sea-state to the total damage. Such calculations tend to show that only few sea-states give the main contribution to the total damage.

The coefficient of contribution is defined as:

$$\gamma_i = pss_i D_{T,i}$$

and the long-term damage rate can be written as:

$$D_t^{LT} = \sum_{i=1}^{N} \gamma_i$$

4.3 Maximum response over a life time T

4.3.1 Distribution function of the maximum

The distribution function of the maximum response over a lifetime T is defined as:

$$f_{MAX}(x, T) = \frac{dP_{MAX}}{dx}$$

where $P_{MAX}(x,T)$ is the cumulative distribution function of the maximum, defined as:

$$P_{MAX}(x, T) = \left(\sum_{i=1}^{N} pss_i P_i(x)^{\frac{T_{SS}}{Tz_i}}\right)^{\frac{T}{T_{SS}}}$$

Where T_{ss} is the duration of the short-term conditions.

If all the cycles are supposed to be independent and considering that the lifetime T is made of a large number of short-term conditions of duration T_{ss}, the cumulative density function of the long-term maximum over a life time T can be written:

$$P_{MAX}(x, T) \approx P_{LT}(x)^{N_T}$$

or

$$P_{MAX}(x, T) \approx \prod_{i=1}^{N} P(x)^{\frac{pss_i T}{Tz_i}}$$

These two last approximations of P_{MAX} are in practice really similar. However, the difference with the exact definition of P_{MAX} above can be important, especially for T< 1 year.

4.3.2 Value exceeded with a risk

The value x exceeded with a risk α is given by:

$$P_{MAX}(\alpha, T) = 1 - \alpha$$

For $\alpha < 0{,}1$, the long-term probability distribution can be written as:

$$P_{LT}(\alpha, T) = 1 - \frac{\alpha}{N_T}$$

4.3.3 Return Period

The quantile 1/e of the maximum response over a life time T is defined as being the return value corresponding to a return period T, hence:

$$P_{MAX}(x_T, T) = \frac{1}{e}$$

4.3.4 Coefficient of contribution

Each sea-state of the scatter diagram does not have the same contribution to the extreme values. Indeed, knowing the short-term distribution for each sea-states, it is possible to evaluate the different contribution.

The coefficient of contribution can be defined for each sea-state as:

$$\gamma_i = pss_i P_i(x)^{\frac{T_{SS}}{Tz_i}}$$

Using this coefficient γ_i, the cumulative distribution function of the maximum cab also be written as:

$$P_{MAX}(x, T) = \left(\sum \gamma_i\right)^{\frac{T}{T_{ss}}}$$

In this formulation, we clearly see that only the sea-states corresponding to γ_i of greater order than 0, are contributing to the extreme values.

SECTION 5 SHORT-TERM STATISTICS

1 General

1.1 Objective

1.1.1 On a given condition (sea-state, navigation speed, unit heading), the objective when performing short-term statistics is to characterize the statistical distribution of the response cycles, hence:

- the entire distribution of response cycles for the computation of fatigue damage
- the tail of the distribution corresponding to the highest cycles, or the statistical distribution of T_{ss} maxima (see Sec 4 for the definition of T_{ss}).

2 Frequency domain calculations

2.1 Linear short-term distribution

2.1.1 Limitations of frequency domain calculations

Linear calculations, widely used for sea-keeping computations, can be performed in frequency domain. It is important to note here that non-linear effects cannot be taken into account in such model.

2.1.2 Rayleigh distribution

From frequency domain computations and assuming that the response spectrum is narrow banded, the response cycles extrema are distributed according to a Rayleigh law:

$$P(x) = 1 - \exp\left(-\frac{x^2}{2m_0}\right)$$

The response cycles ranges are distributed according to a Rayleigh law:

$$P(\Delta x) = 1 - \exp\left(-\frac{(\Delta x)^2}{8m_0}\right)$$

As explained in Sec 4, [3.2.2], the mean zero up-crossing period T_z is also known.

2.2 Short-term maximum

2.2.1 Extrapolation of the distribution

The expected maximum is given by:

$$x_{1/n} = \sqrt{2m_0 Ln\left(\frac{T}{T_z}\right)}$$

Since the distribution is known analytically (see [2.1.2]), it could be extrapolated to any probability level. The short-term maximum can be computed for any duration T and risk level α:

$$X_{MAX}(T, \alpha) = \sqrt{-2m_0 Ln\left(1 - (1-\alpha)^{\frac{Tz}{T}}\right)}$$

2.2.2 Short-term maximum distribution

When the number of cycles (N>800) is important, the distribution of the short-term maximum tends to a Gumbel distribution:

$$P_{MAX}\left(x, \frac{T}{Tz}\right) \approx \exp\left[-\exp\left(\left(\frac{x_{1/N} - x}{x_{1/N}}\right) 2Ln\frac{T}{Tz}\right)\right]$$

It is to be noted that the Gumbel model is only an approximation and that it is only valid for the body of the distribution, hence for:

$$-0.165 < \left(\frac{x_{1/N} - x}{x_{1/N}}\right) < 0.125$$

2.2.3 Most Probable Maximum of Gumbel distribution

The Most Probable Maximum of the Gumbel distribution is equal to the expected maximum, hence:

$$MPM = x_{\frac{1}{N}} = \sqrt{2 m_0 Ln\left(\frac{T}{Tz}\right)}$$

2.3 Fatigue damage

2.3.1 Computations of short-term fatigue damage

Short-term fatigue damage rate can be computed analytically:

- for single slope S-N curve:

$$D_t^{ST} = \frac{1}{KT_Z}(2\sqrt{2m_0})^M \Gamma\left(1 + \frac{M}{2}\right)$$

  where K is the characteristic constant of the S-N curve, and M is the characteristic inverse slope of the S-N curve.

- for multi slope S-N curve:

$$D_t^{ST} = \frac{1}{T_z}\sum_{j=1}^{Nslope}\frac{1}{K_j}(2\sqrt{2m_0})^{M_j}\left(\Gamma\left(1 + \frac{M_j}{2};\frac{S_{Q_j}^2}{8m_0}\right) - \Gamma\left(1 + \frac{M_{j-1}}{2};\frac{S_{Q_{j-1}}^2}{8m_0}\right)\right)$$

  where:

  K_j : Characteristic constants of the S-N curve

  M_j : Characteristic inverse slopes of the different segments of the S-N curve

  S_{Qj} : Stress range, in N/mm², at the number of cycles corresponding to the change of slope (slope intersection). It is to be noted that S_{Qj} corresponds to the low part of the domain j, hence:

  $$N_j(\Delta\sigma) = K_j \Delta\sigma^{-M_j}$$

  if $\Delta\sigma > S_{Qj}$

  $\Gamma(1+X ; S)$: Upper incomplete gamma function defined by:

  $$\Gamma(1 + X;S) = \int_S^{\infty} t^X e^{-t} dt$$

3 Time domain computations

3.1 Non-linear process

3.1.1 The assumptions of linearity is not valid for all types of loads and structure responses (2nd order wave loads, drag forces, etc.), time domain computations are used to model non-linear process.

From time domain computations, the assumptions of a Rayleigh law to describe the peak distribution (as described in Sec 4, [4.1.1]) cannot be used. It appears here that the main issue regarding time domain computations is that the distribution of extreme remains unknown. The following lines present the method to derive and study this distribution.

When performing time domain simulations, attention is to be paid to the potential issues caused by transient phases.

3.2 Empirical short-term extreme distribution

3.2.1 Up-crossing analysis

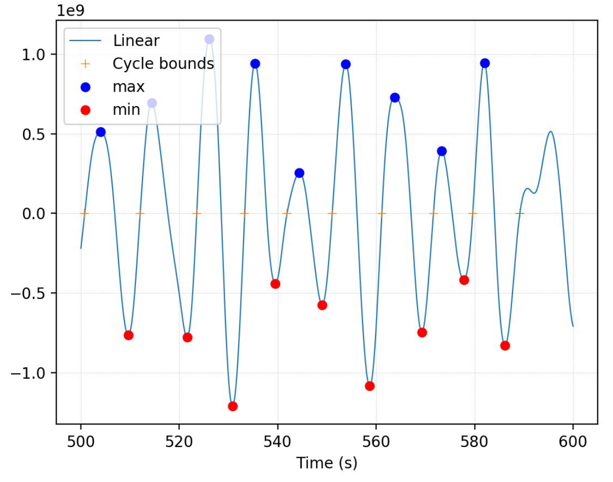
The first step consists in deriving a short-term extreme distribution from a time-domain simulation of finite duration T, using an up-crossing analysis.

N cycles in the duration T are defined, a cycle being defined between two up-crossing of the mean value (see Fig 1). Each of these cycles if characterized by a period T(i).

The mean up-crossing period can then be defined as:

$$T_z = \frac{1}{N}\sum_{i=1}^{N} T(i)$$

Figure 1 : Up-crossing analysis



3.2.2 Pre-processing before the up-crossing analysis

Depending on the type of simulations to be studied, the signal can be pre-processed before the up-crossing analysis. For instance, a low-pass (or band-pass) filter can be applied to filter noise and facilitate the up-crossing analysis.

In some specific case, the simulations can also be compared to a linear simulation to be studied. This method is presented in [3.2.4].

3.2.3 Empirical distribution

From the up-crossing analysis and the defined N cycles, an empirical distribution (see Fig 2) can be defined considering the following assumption: each extreme value is independent from each other. The cycles are sorted in decreasing order and each cycle is given the exceedance rate i/(N+1).

3.2.4 Particular case

A particular case, as explained in [3.2.2], may be identified and used to help to define the non-linear short-term distributions. The main idea of this approach is to compare the time series of a linear simulation with the simulation including the non-linearities, as shown on Fig 3 and Fig 4.

It is absolutely necessary that the linear and non-linear simulations are done with exactly the same wave time serie input.

To allow the comparison between the short-term distribution built from the two time series, the upcrossing analysis has to be done on the same cycles. The cycles are defined from the linear time serie, the same cycles are used to extract the minimum, maximum and range from the non-linear time serie. The aim is to obtain the exact same number of events in both simulations.

As it has been explained in [2.1.2] and [3.1.1], the distribution of linear extremes fit the theoretical Rayleigh distribution, whereas the distribution of non-linear extremes diverge from the Rayleigh distribution.

In order to facilitate the comparison, the following function can be defined:

$$\frac{X_L}{X_{NL}} = f(X_{NL})$$

where X_L and X_{NL} are taken at the same exceedance rate. The function $f(X_{NL})$ quantifies the degree of non-linearity.

Once the empirical function $f(X_{NL})$ is defined, it is possible to fit an analytical function $g(X_{NL})$ on $f(X_{NL})$ as shown on Fig 5. This function g is fitted to avoid the numerical issue close to 0.

Finally, it is possible to define the non-linear distribution using the function g and the Rayleigh distribution of the linear extremes:

$$\nu(x_L) = \frac{1}{T_z}\exp\left(-\frac{x_L^{\,2}}{2m_0}\right)$$

$$\nu(x_{NL}) = \frac{1}{T_z}\exp\left(\frac{-(g(x_{NL})x_{NL})^2}{2m_0}\right)$$

The convergence issue impose to consider only the converged part of the distribution, and to exclude the tail. More details regarding convergence and calculation times issue are presented in [3.2.5].

Figure 2 : Empirical distribution

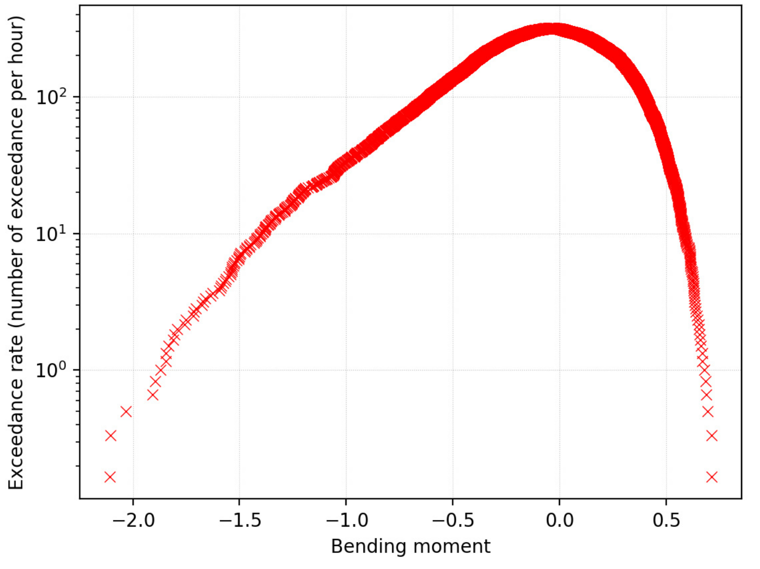


Figure 3 : Time series of compared signals

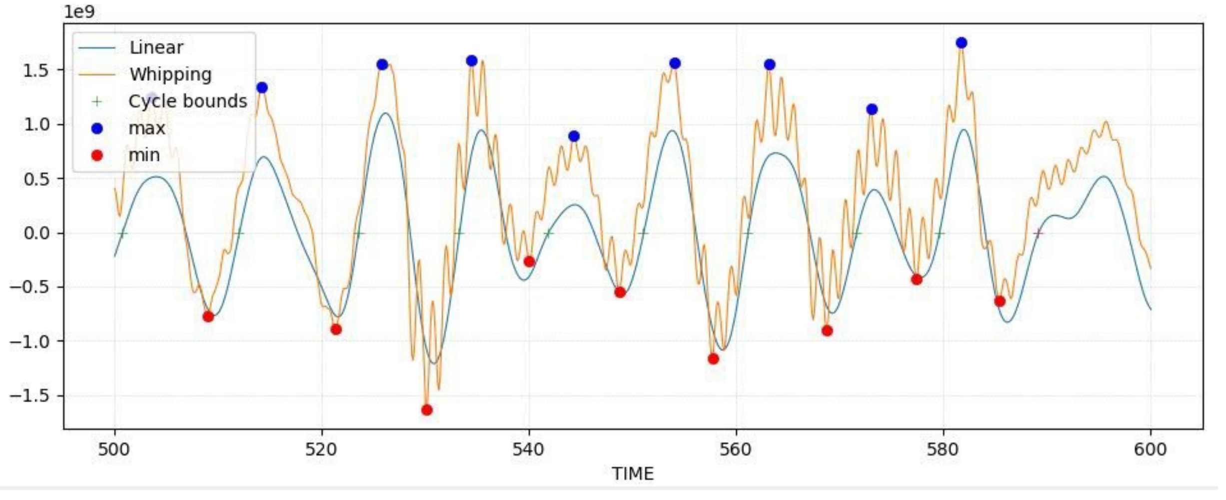


Figure 4 : Compared distributions

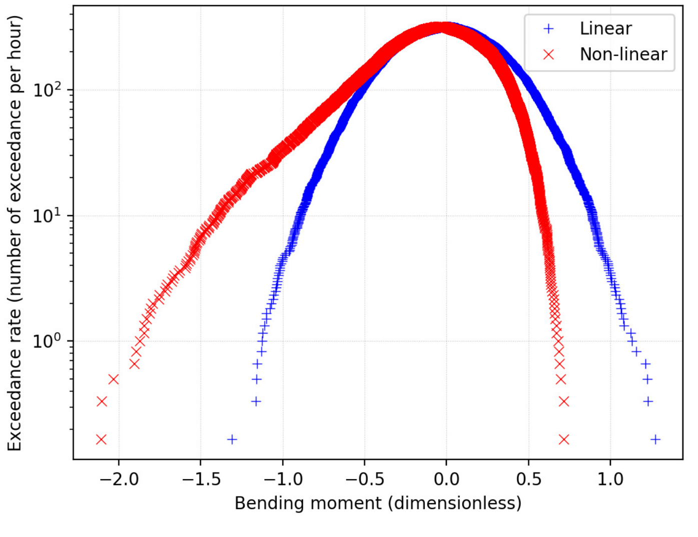
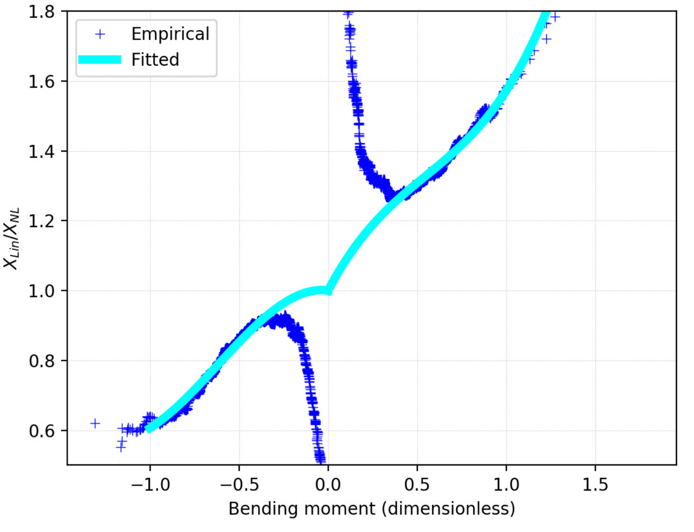


Figure 5 : Functions $f(X_{NL})$



3.2.5 Calculations times issue

It is important to note that the tail of the empirical distribution is not converged. In particular, due to the up-crossing analysis, no data are available for RP > T.

When looking for a specific point at a given RP, the easiest method would be to simply interpolate between the two closest points given by the empirical distribution. However, the level of confidence decreases drastically as RP increases.

As a rule of thumb, it can be considered that the data converge only where RP < T/20, whereas we have only a poor convergence for T/20 < RP < T. The problem occurring here is then the need for a very long simulation when longer RP are requested.

Different approaches to calculate extreme values corresponding to high RP are presented in [3.3].

3.3 Tail of the distributions

3.3.1 Parametric approach: fitted distributions

The following solution proposed to the convergence and calculations times issues detailed in [3.2.5] is to fit a analytical distribution on this empirical distribution.

These parametric approach imposes to force the analytical distribution to fit to the empirical data. For the fit, several methods are available such as the maximum likelihood method, the method of moments, the method of L-moments, the least square method.

Several analytical distribution can be used to fit the empirical distribution. The three parameters Weibull distribution is often used:

$$P(x) = 1 - \exp\left(-\left(\frac{x - x_0}{K}\right)^{\beta}\right)$$

where K, x_0 and β are the parameters or the Weibull distribution.

Thanks to the fit, results are available for RP > T and a better convergence is reached for RP < T. A proper level of confidence has to be calculated for the fit. Several methods, such as the bootstrap method, are available in the literature.

It is important to note that the results will depend on the analytical law being fitted and that a possible bias is introduced as the unknown distribution may be quite different from the analytical distribution used for the fit.

3.3.2 Artificially increased wave height

The second approach proposed here is to artificially increase the number of empirical points useful for the calculations of the extreme value.

The main principle is to perform the simulations on a sea-state with an increased wave height λHs, and the empirical distribution $\nu'(x)$ is computed (see Fig 6).

The distribution on the initial sea-state is given by:

$$\nu(x) = \frac{1}{T_z}(T_z \times \nu'(x))^{\lambda^2}$$

This relationship is fully exact in the case of linear Rayleigh distributed extremes.

$$\nu'(x) = \frac{1}{T_z}\exp\left(-\frac{x^2}{2\lambda^2 m_0}\right) = \frac{1}{T_z}\left(\exp\left(-\frac{x^2}{2m_0}\right)\right)^{1/\lambda^2}$$

$$\nu'(x) = \frac{1}{T_z}(T_z \times \nu(x))^{1/\lambda^2}$$

If the relation $x_L = f(x_{NL}) \cdot x_{NL}$ (f being defined as per [3.2.4] is the same for both sea-states (the initial sea-state Hs and the increased sea-states λHs) then this relationship is exact even in the case of non-linear extremes.

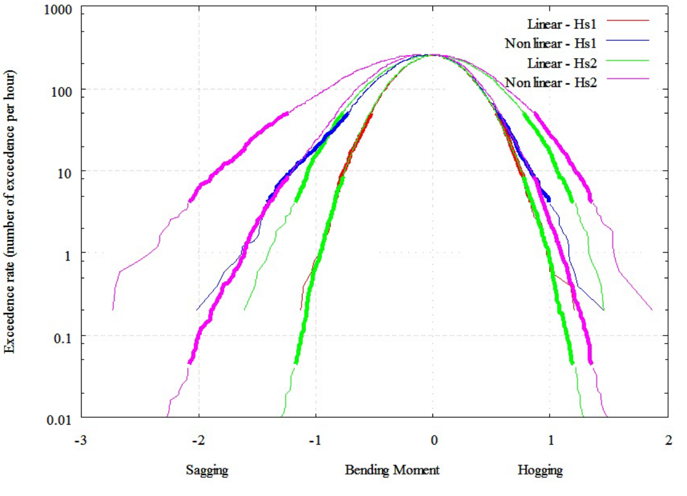
$$\nu(x_{NL}) = \nu(x_L = f(x_{NL})x_{NL}) = \frac{1}{T_z}(T_z\nu'(x_L = f(x_{NL})x_{NL}))^{\lambda^2}$$

$$\nu(x_{NL}) = \frac{1}{T_z}(T_z \cdot \nu'(x_{NL}))^{\lambda^2}$$

In practice, this method has to be used only with the tail of the distribution:

$T_z \cdot \nu'(x) < 0.2$

Figure 6 : Increased wave height



3.4 Statistics of extremes

3.4.1 General

Different methods to evaluate short-term extreme responses over a duration T are presented hereafter. The aim here is to described $P_{MAX}(x)$ (as defined in Sec 4, [2.3.1]) without using the individual maxima distribution P(x), but only the 3 hours maxima overall several realizations.

3.4.2 Independence of the cycles

In [3.1], [3.2] and [3.3], some methods have been presented to analytically define the distribution of the cycle maxima P(x) from the empirical distribution. These approaches are based on the assumptions of independence of the cycle maxima, as explained in [3.2.3]. Under these assumptions, the distribution $P_{MAX}(x,N)$ can then be analytically derived from the known P(x) distributions.

However, the assumption of independence is not fully valid and alternative methods have been developed to described the distribution $P_{MAX}(x,N)$.

3.4.3 Empirical cumulative distribution function

The empirical cumulative distribution function can be built by computing several independent extremes from several independent simulations.

Fig 7 presents a comparison between a distribution of 3 hours maxima (20 simulations) and a distribution of cycle extrema from a 60 hours simulations. It can be noted here that even if the cycle extrema distributions present a large number of points, the "interesting" zone (the tail of the distribution) is not better defined.

3.4.4 Statistical values

Several statistical values such as the mean maximum value, MPM, a quantile α (see Sec 4, [2.3]) can be defined to characterize the distribution function.

3.4.5 Fitted analytical distribution

In order to enhance the convergence, analytical distribution can also be fitted to the empirical distribution.

The Generalized Extreme Value (GEV) distribution is often used to describe short-term maximum distribution. The Gumbel distribution is one specific case of GEV.

As per the cycle extrema distributions, the evaluation of uncertainties has to be performed.

3.5 Evaluation of uncertainties

3.5.1 Convergence study

Several methods exist to study the convergence and the extrapolation uncertainties, such as the bootstrap technique, the shorter simulations technique or the approximate normality of the maximum likelihood estimator.

In this Section, we will develop the bootstrap and the shorter simulations techniques.

3.5.2 Bootstrap technique

The idea is to generate artificial distributions from the original extreme dataset. Basically, the first step is to perform several random sampling with replacement. It is to be noted here that some data points may be duplicated, and others data points from the initial dataset be omitted in a bootstrap sample.

Once this new distributions are created from the random sampling described above, short-term extremes can be extrapolated, as it has been done for the original distribution. From these several short-term extremes, it is now possible to define the distribution of these short-term extreme extrapolation, as shown on Fig 7.

These distribution are the uncertainties distribution of these short-term extreme, from all bootstrap samples. These distributions can be used to characterized the uncertainties on the initial value.

3.5.3 Shorter simulations techniques

The idea is to go back to the time domain simulation and to divide it in N shorter simulations (N could be for instance taken equal to 10). From theses N shorter simulations, typically 3 hours, N short-term extremes can be deduced.

The standard deviation σ of this N extremes is computed. Finally the uncertainties are characterized by the ratio:

$$\frac{\sigma}{\sqrt{N}}$$

3.5.4 Estimation of short-term maximum

This sub-article presents a method to safely estimate the short-term maxima.

As explained in Sec 4, [2.1]the short-term variability imposes that the short-term maximum is entirely described by its probability density function $f_{MAX}(X)$ (or its cumulative density function).

However for design purpose a specific characteristic value is used. Usually the mean maximum or the most probable maximum (MPM) are used, but the median (corresponding to 50% probability of non exceedance), the 80% percentile P (80% probability of non exceedance) or higher percentiles can also be used.

Computing time constraints impose to evaluate this characteristic value X_t from a limited number of N simulations. Because N is usually small, the estimation X_{est} of the characteristic value may not be accurate. However, this estimation can be corrected to ensure that the final (or corrected) estimation X_{corr} will be at least equal to the target value with a certain level of confidence. On the basis of the following formulation:

$$X_{cort} = X_{est} + \frac{\alpha}{\sqrt{N}}\sigma_{est}$$

where σ_{est} is the standard deviation of the N estimations, and α is function of N that can be calibrated from analytical or empirical distributions. Tab 1 give values of α for the 50% quantile, the 80% quantile and the 90% quantile, corresponding to a 90% confidence level, hence:

$$P\left(X_{est} + \frac{\alpha}{\sqrt{N}}\sigma_{est} > X_t\right) = 0.9$$

It is also to be noted that the values of α have been derived assuming that P_{max} follows a Gumbel distribution. They are given here as an illustration of the type of calibration that can be performed.

Figure 7 : Bootstrap techniques

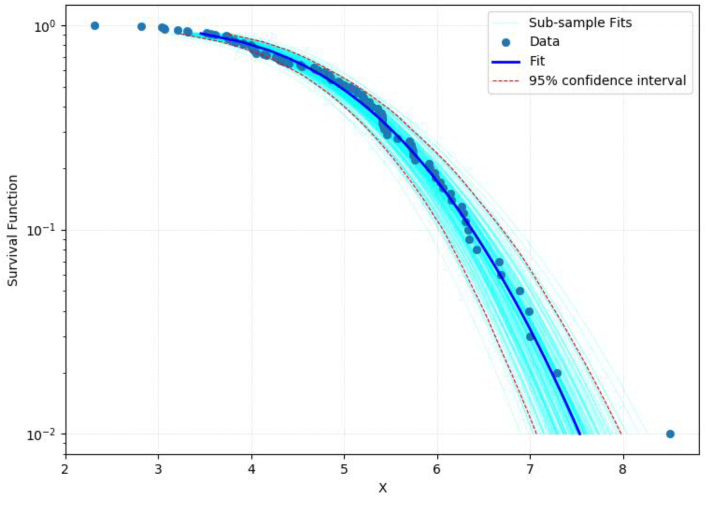


Table 1 : Values of α with a 90% level of confidence

	α (calibrated for a 90% level of confidence)				
Quantile (Q)	N = 5	N = 10	N = 20	N = 30	N = 50
50% (median)	1,77	1,62	1,60	1,60	1,60
80%	3,92	3,08	2,72	2,59	2,46
90%	5,87	4,73	4,20	4,07	3,82

3.6 Fatigue calculations

3.6.1 Rainflow counting

For fatigue computations, all cycles have to be taken into account. The rainflow cycle counting method can be used to define the short-term cycle ranges distribution. Definitions of the rainflow counting method are presented in NI 611, Guidelines for Fatigue Assessment of Steel Ships and Offshore Units, Section 11. More details on this method can also be found in ASTM E1049-1985, and ISO 12110-2.

3.6.2 Miner sum

Once the cycle ranges distribution is known, a Miner sum can be used to compute the damage, such as:

$$D = \sum_{i=1}^{Ncycles} \frac{1}{N(\Delta\sigma_i)}$$

3.6.3 Convergence and damage contribution

The highest cycles are not converged, however these highest cycles do not correspond to the largest part of the damage.

For a Rayleigh distribution with an S-N curve (M=3):

- 10% of the damage is due to the highest 1% cycles
- 1% of the damage is due to the highest 0.05% cycles.

On this example, it appears clearly that the contribution of the highest cycles is low. For a simulation of 1000 cycles:

- the 10 highest cycles are not converged, but they contribute to less than 10% of the damage
- the 990 lowest cycle are nearly converged and contribute to 90% of the damage.

As a rule of thumb, a 1000 cycles simulations (about 3 hours) is considered as a minimum to correctly assess the fatigue damage.

4 Equivalent design wave approach (EDW)

4.1 General

4.1.1 Objectives

As all the short-term approaches previously presented, the Equivalent Design Wave (EDW) approach aims at reducing the computing time. Using this method, the basic idea is to reduce the short-term simulations to a limited number of very short duration wave events. The short-term (and long-term) extreme or damage are computed from these results.

4.1.2 Definition

The EDW is a wave, or a group of waves, defined in order to create a given response, the probability level of which is known. This given response is called the governing parameter of the EDW. It is often a load parameter (such as vertical bending moment, acceleration...) but it can be any type of unit response (local pressure, stress...).

In a first step, one or several governing parameters, having a major influence on the stress in the considered structural detail, are identified, using experience or simplified analysis models. If several governing parameters are identified, then several EDWs are to be used, each of them being based on one parameter.

The governing parameters are to be quantities that can be evaluated by a linear model, so that their statistical distributions can be determined by spectral analysis. The EDW for one governing parameter and one probability level is then defined, in such a way that, when this EDW is applied on the linear model, the response for the EDW parameter is equal to its expected value at the defined probability level. All the EDWs are then simulated with the non-linear model in time domain, and the non-linear response at the considered probability level is the maximum non-linear response among all the EDWs.

In most cases, the governing parameters are the linearized hydrodynamic loads acting on the structure: pressure, accelerations, and global loads for slender units. The governing parameters can also be based on the structural response, such as the linearized stress in the structural detail.

Several types of EDWs exist, such as:

- Regular Design Wave (RDW), see [4.2]
- Response Conditioned Wave (RCW), see [4.3]
- Directional Response Conditioned Wave (DRCW), see [4.4].

General practice in the industry is to choose a RDW, the main advantage being the simplicity. However, irregular design wave such as RCW and DRCW are more and more used, as they are a better representation of irregular sea-states. The main idea is to include both wave spectrum and ship response in the definition of the Design Wave.

There are two major applications of design waves, both aiming at reducing the duration or the number of computations, by reducing a large number of irregular sea-states in a few number of wave events:

- the evaluation of the non-linearity of the hydrodynamic loads, with the EDW maximizing a linear load
- the evaluation of the extreme structural response, with the EDW maximizing a load parameter.

4.1.3 Evaluation of non-linear effect

The first application takes place in the evaluation of non-linear effects. When the hydrodynamic loads and the unit structural response are supposed to be linear, transfer functions can be computed, and extreme response can be derived very easily using a Rayleigh distribution. However, when the hydrodynamic loads are not linear it is not possible any more to simulate long duration, because of a prohibitive CPU time required by the more refined hydrodynamic model.

In this case, the simulations can be reduced to a few numbers of Design Waves, which are calculated to create a given linear response corresponding to a given return period. The non-linear response computed on these waves is supposed to have the same return period. It has been shown in several papers that RCWs are performing quite well in the evaluation of wave non-linear effects and whipping effects on the vertical bending moment.

4.1.4 Extreme structural response

Another application of EDWs is to save time by reducing the number of structural computations. When the structural response and the hydrodynamic loads are supposed to be linear, it is possible to compute stress RAOs for all the structural details in the ship, and from there to compute either fatigue damage or extreme stress.

However, these calculations require a quite high number of structural computations (twice number of frequencies time number of headings). To reduce this number, the usual practice is to select a number of governing loads, to define the EDWs that are maximizing these loads, and to compute the structural response only on those waves. It is here assumed that a strong relationship exists between the chosen governing loads and the stress response. Hence the accuracy of this method highly depends on the choice of the governing parameters.

It could also be noted that in the general case, both the hydrodynamic loads (non-linear wave forces) and the structural response (buckling check) are considered to be non-linear. The EDW method here combines the two advantages of reducing the required number of structural computations and allowing using a more complex hydrodynamic simulation.

4.2 Regular design wave (RDW)

4.2.1 Definition

For a given response, the main design wave requirement is that the linear response on this wave is equal to a targeted value at a given time. An infinity of waves satisfy this requirement, the simplest being a regular wave, with a heading and a frequency to be determined from the governing parameter Linear Transfer Function (LTF) or from its response spectrum for the considered short-term condition. In case of long-term analysis, the response spectrum for the short-term condition with the highest contribution to the long-term value is used. The EDW amplitude is then obtained by dividing the target response by the amplitude of the LTF at the selected heading and frequency. This type of design wave is not suited for multi modal sea states for which it is recommended to use DRCW (see [4.4.1]).

The regular EDW (see Fig 8) is characterized by the following four parameters:

β_{EDW} : Regular EDW heading. β_{EDW} can be taken as:

- the main wave heading of the considered sea-state, or
- the wave heading associated with the maximum of $|LTF(\omega,\beta)|$

ω_{EDW} : Regular EDW frequency. ω_{EDW} can be taken as:

- the frequency of the maximum of the response spectrum, or
- the frequency of the maximum of $|LTF(\omega,\beta)|$

A_{EDW} : Regular EDW amplitude, taken equal to:

$$A_{EDW} = \frac{X}{|LTF(\omega_{EDW}, \beta_{EDW})|}$$

φ_{EDW} : Regular EDW phase, taken equal to:

$$\varphi_{EDW} = -\text{phase}(LTF(\omega_{EDW}, \beta_{EDW}))$$

where:

X : Target response value

$LTF(\omega,\beta)$: Linear transfer function of the governing parameter.

It can be noted here that the RDW imposes that two parameters, (β_{EDW}, ω_{EDW}) should be defined.

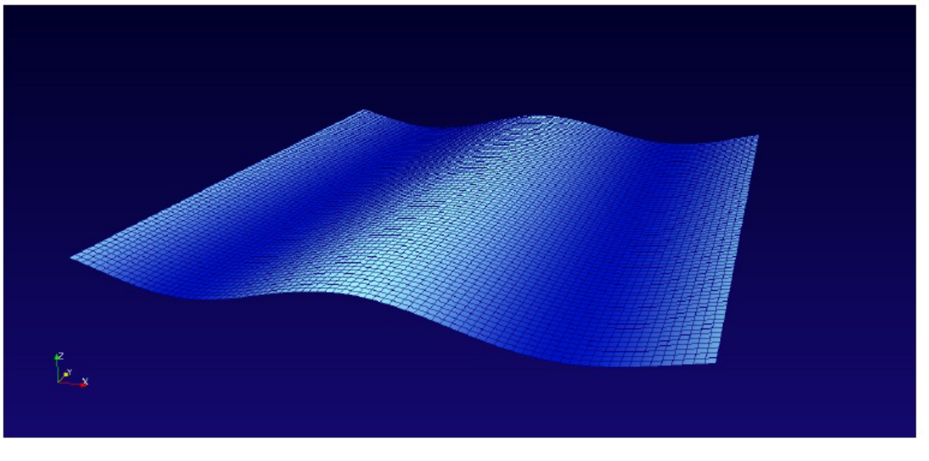
4.2.2 Limitations and possible improvements

There are different ways to define the heading and period of a regular design wave:

a) The usual practice is to select the heading and period of the wave in order to maximize the RAO. Its drawback is that the period and heading of the selected RDW does not depends of the meteocean data. In particular, the maximum of the RAOs might be located at a frequency / heading where there is no wave energy. Such a RDW might thus not be representative of the actual waves responsible for the extreme response.

   For some response, heading would thus have to be manually tuned, like for instance for the wave bending moment, which sometimes presents a maximum at quite high frequency at 60° which is a heading that actually does not contribute to the long-term value.

Figure 8 : Regular Design Wave



b) To overcome this issue, one might suggest that a way to automatically select frequency and heading could be done by determining which frequency/heading contribute the most to the long-term extreme, and select those frequency/heading as parameters for the RDW.

However, due to the spreading of the actual sea-state spectrum, this could lead to very inaccurate results, as shown in Fig 9. This argument applies the same way for both heading and frequency. Vertical shear force usually illustrates this issue: for a typical ship, the heading contributing the most to the long-term value is 180°, where the RAO is actually quite weak (see Fig 10).

c) A possible improvement to avoid manual tuning of the heading would be to select the heading contributing the most to the long-term value, but on a calculation that would have been previously performed without spreading (to avoid the problem explained in b). The frequency chosen remaining based on the RAO maximum.

Figure 9 : RAO and Wave Spectrum

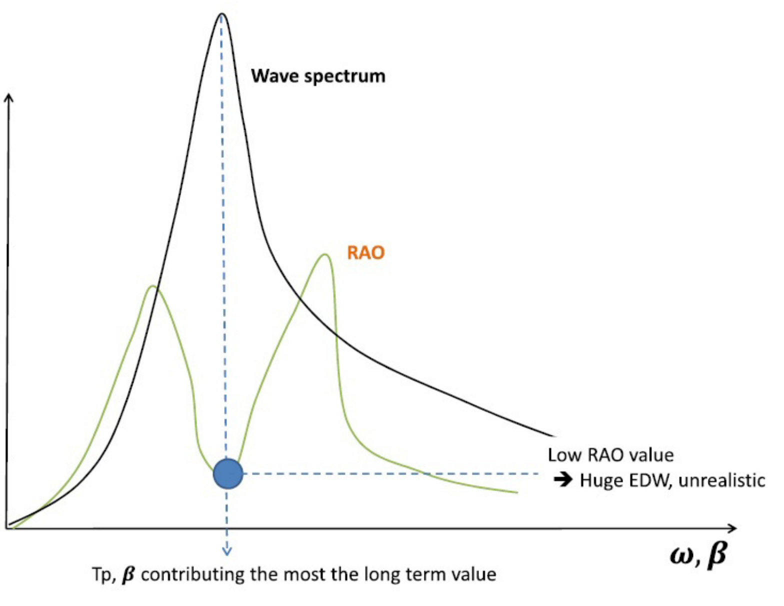


Figure 10 : Heading contribution to the long-term value

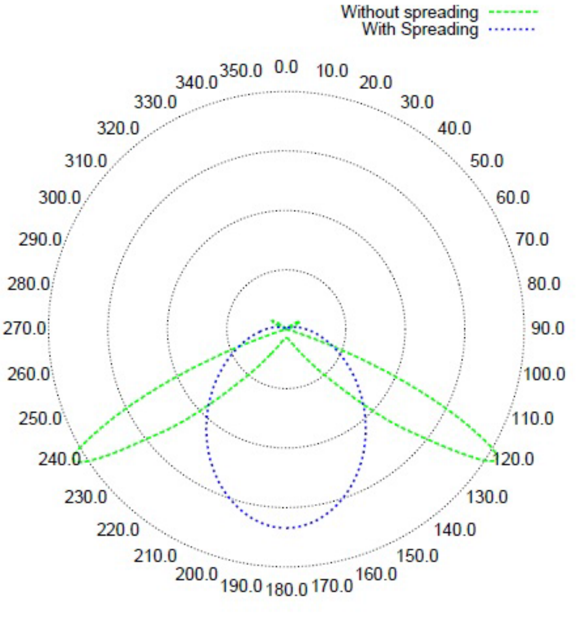
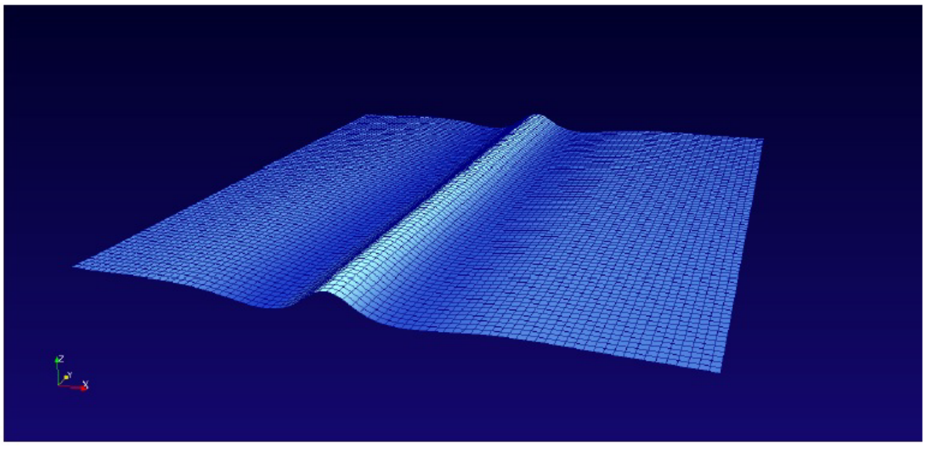


Figure 11 : Response Conditioned Wave



4.3 Response conditioned wave (RCW)

4.3.1 Definition

The response conditioned wave (see Fig 11), also called irregular long-crested EDW, is defined as the wave train leading to the mean of all the possible responses targeting a given value, on an unidirectional sea-state. This EDW is thus an irregular wave train, containing several components, the amplitude/frequency/phase of these components can be computed from the RAO and wave spectrum. This type of EDW is then characterized by the following four parameters:

β_{EDW} : EDW heading. β_{EDW} can be taken as the main wave heading of the considered sea-state

ω_i : Frequency of the EDW component i. The values of ω_i are chosen in order to discretize the wave frequency range, following the recommendations given in [4.2.1]

A_i : Amplitude of the EDW component i, taken equal to:

$$A_i = S_\eta(\omega_i) \cdot |LTF(\omega_i, \beta_{EDW})| \frac{X}{\lambda_0} \Delta\omega_i$$

φ_i : Phase of the EDW component i, taken equal to:

$$\varphi_i = -\text{phase}(LTF(\omega_i, \beta_{EDW}))$$

where:

X : Target response value

$LTF(\omega,\beta)$: Linear transfer function of the governing parameter

$S_\eta(\omega)$: Wave energy density spectrum

λ_0 : Zero order moment of the governing parameter response spectrum (see Ch 1, App 1, [4.1.2])

$\Delta\omega_i$: Frequency step associated with ω_i in the frequency discretization.

4.3.2 Advantages and limitations

The wave being unidirectional, the question about which heading should be selected is the same as for the regular waves. One advantage of such RCW is that it contains both RAOs and wave data, which will lead to a more realistic wave.

4.4 Directional response conditioned wave (DRCW)

4.4.1 Definition

The RCW described in [4.3] is unidirectional, but it can be generalized to model irregular short-crested seas (or multi-modal). The irregular response conditioned wave, also called directional response conditioned wave (see Fig 12), is thus defined as the wave train leading to the mean of all the possible responses targeting a given value, on a directional sea-state. This EDW is then a response conditioned wave that accounts for the wave energy spreading in the sea-state.

The irregular short-crested EDW (or DRCW) is characterized by the following four parameters:

β_j : Heading of the EDW component (i,j). The values of β_j are chosen in order to discretize the wave energy direction range, following the recommendations in Sec 11, [4.2.1]

ω_i : Frequency of the EDW component (i,j). The values of ω_i are chosen in order to discretize the wave frequency range, following the recommendations in Sec 11, [4.2.1]

$A_{i,j}$: Amplitude of the EDW component (i,j), taken equal to:

$$A_{i,j} = S_\eta(\omega_i, \beta_j) \cdot |LTF(\omega_i, \beta_j)| \frac{X}{\lambda_0} \Delta\omega_i \Delta\beta_j$$

$\varphi_{i,j}$: Phase of the EDW component (i,j), taken equal to: $\varphi_{i,j} = -\text{phase}(LTF(\omega_i, \beta_j))$

where:

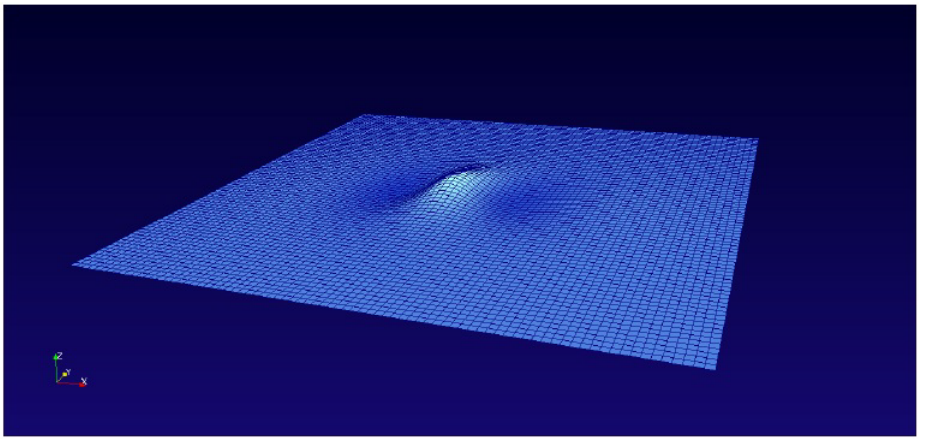
X, LTF(ω,β) : As defined in Ch 1, App 1, [5.5.3]

$S_\eta(\omega,\beta)$: Wave energy density spectrum including directional spreading

λ_0, $\Delta\omega_i$: As defined in Ch 1, App 1, [5.5.3]

$\Delta\beta_j$: Wave heading step associated with β_j in the heading discretization.

Figure 12 : Directional Response Conditioned Wave



SECTION 6 LONG-TERM APPROACHES

1 General

1.1 Objectives

1.1.1 The objective when performing a long-term approach is to characterized the statistical long-term distribution of the response cycles, hence:

- the entire long-term distribution of response cycles for the computation of fatigue damage
- the tail of the distribution corresponding to the highest cycles.

1.1.2 The objective of all the long-term methods presented in this section is to obtain the long-term statistics (see Sec 4, [4]) in the most efficient and accurate way.

1.2 Fully linear long-term analysis

1.2.1 The unit short-term distribution Pi(x) (as defined in Sec 4, [4.2] and Sec 4, [2.2]is computed on every sea-state of the operating conditions, hence for all the cells of the scatter diagrams, and for all heading. Knowing Pi(x) for each condition, nLT(x) and Pmax(x,T) can be computed (see Sec 4, [4.2] and Sec 4, [4.3]).

This ideal solution, as presented in Article [2] would impose to simulate all the ship life with a time domain non-linear code, including all the non-linearity (slamming, Froude-Krylov forces...)

It appears clearly that this solution is impossible to apply, because of the huge computations time involved by non-linearities. For fully non-linear problems, this solution can however be considered.

As it will be later explained, this direct approach is often used as a first step for more long-term analysis.

1.3 Limitations

1.3.1 Computing time

Except for fully linear analysis (see Article [2]), this solution is not practical, as it will lead to huge computing time. Indeed, non-linear time domain simulation are often even slower than real time.

Since the fully long-term analysis can only be used with linear model, all non-linear effect are neglected. However, depending on the physical quantity being analyzed, some non-linearities should be taken into account.

1.3.2 Need for alternative approaches

Taking into account these limitations, alternative approaches have been developed in order to perform long-term calculations. As an example, a simplified linear approach through RAOs can be used if the ship response remains linear. It is also possible to use a linear approach to select a reduced number of sea-states contributing to the extreme or damage, and to study these specific sea-states with time-domain solution.

In practice, the different methods usually combine a linear long-term analysis with some corrections to take into account some non-linear effects.

1.4 Alternative short-term approaches

1.4.1 General

The basic idea is to reduce the simulations to a limited number of short-term sea-state, and to compute the long-term extreme and the long-term damage from these short-term results.

Different approaches can then be developed to select the sea-states contributing to extreme/damage, or to built a sea-state maximizing a certain quantity (Design sea-state).

1.4.2 Different methods for long-term analysis

Three different methods will be presented in this section, such as:

- multiple design sea-states, as detailed in Article [3]
- single design sea-state, as detailed in Article [4]
- envelope sea-states, as detailed in Article [5].

For these different approaches, both advantages and limitations will be detailed. Practical examples will also be given in order to illustrate these methods.

2 Linear spectral approach

2.1 Method

2.1.1 With a linear approach, as it has been shown in the Sec 5, [2.1], the short-term distribution Pi(x) is analytically known (Rayleigh distribution) for every sea-states. Since the RAOs can be computed for every frequency, heading and speed with low CPU cost, Pi(x) can be easily obtained.

The extreme response is then computed for any duration and risk and the fatigue damage can also be calculated.

Thanks to this fully long-term analysis, the contribution of the different sea-states to the extreme response and the damage can be evaluated (see Sec 4, [4.2.2] and Sec 4, [4.3.1]. Eventually, more accurate simulation models (trying to include non-linearities) can then be used with a group of sea-states selected from the fully-linear analysis.

3 Multiple design sea-states

3.1 Method

3.1.1 General

The multiple design sea-states method aims at reducing the number of required computations. The main idea here is to perform calculations only on sea-states identified as critical, hence for which the coefficient of contribution γ_i>>0, and eventually to be able to extrapolate the results to other sea-states.

3.1.2 Steps of the approach

Using frequency domain calculations, a fully linear direct analysis is first performed on all sea-states. From this computation, a group of sea-states giving the main contributions to the damage/extreme is identified. In the contribution graph (see Fig 1 and Fig 2), a number of sea-state/headings can be clearly highlighted.

The second step of the approach is to perform simulations including non-linearities, hence involving more complex model, on the selected sea-states/headings in order to correct $P_i(x)$. The corrected results from these selected sea-states are interpolated/extrapolated to the remaining sea-states/headings in order to get the correction on all sea-states. It has to be checked that the most contributive conditions are inside the chosen conditions. If not, new sea-states/headings are chosen and the process started again.

Examples of application cases for both extreme and fatigue are presented in the App 2.

Figure 1 : Damage contribution

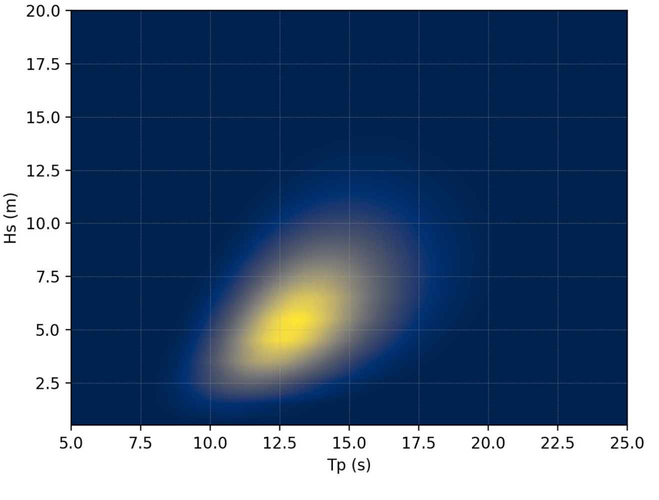
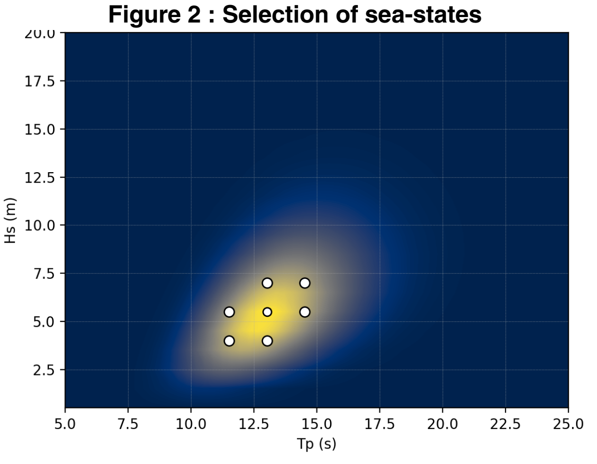


Figure 2 : Selection of sea-states



4 Single design sea-state

4.1 Method

4.1.1 General

The single design sea-state approach (see Fig 3 and Fig 4) is similar to the multiple design sea-states approach (see Article [3]) except that only one sea-state is selected. This single design sea-state is first chosen from linear spectral analysis, and non-linear simulations are then performed on it.

For computations of extremes, the short-term extreme is supposed to be the long-term extreme.

For fatigue computations, the non-linear/linear damage ratio is applied to long-term linear damage.

Figure 3 : Design sea-state for extreme

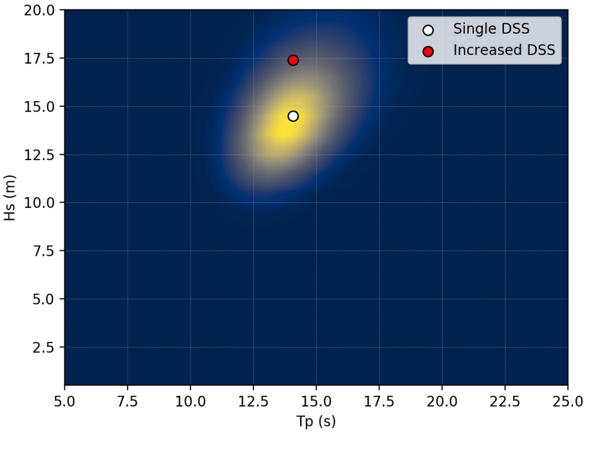
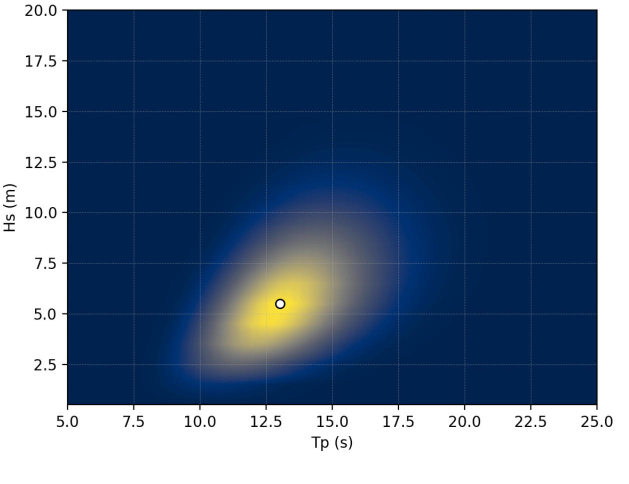


Figure 4 : Design sea-state for fatigue



5 Envelope sea-states

5.1 Method

5.1.1 General

Using the envelope sea-states approach, the simulations will be performed only on an envelope of sea-states (also called environmental contour) corresponding to a given return period. The extreme responses are computed from these sea-states.

5.1.2 Generation of envelope sea-states

The I-FORM approach is used to determine envelope sea-states from scatter diagrams. The envelope is defined in the environmental parameters space (usually Hs, Tp) and corresponds to a specific return period, hence a risk α (see Sec 4, [4.3.2]), and a specific sea-state duration T_{ss}.

The I-FORM approach and the methodology to derive such contours are fully described in the App 1.

On each of the sea-states defined by the contour, the maximum response is computed, as explained in Sec 4. The maximum response over a duration T_{ss} is taken over all these sea-states. The duration of the sea-state T_{ss} is usually 3 hours (see Fig 5).

The actual practice of the offshore industry is to consider the Most Probable Maximum (MPM), but it is not justified by the I-FORM method and neglects the short-term variability (see App 1, [2.2.1]).

5.2 Limitations

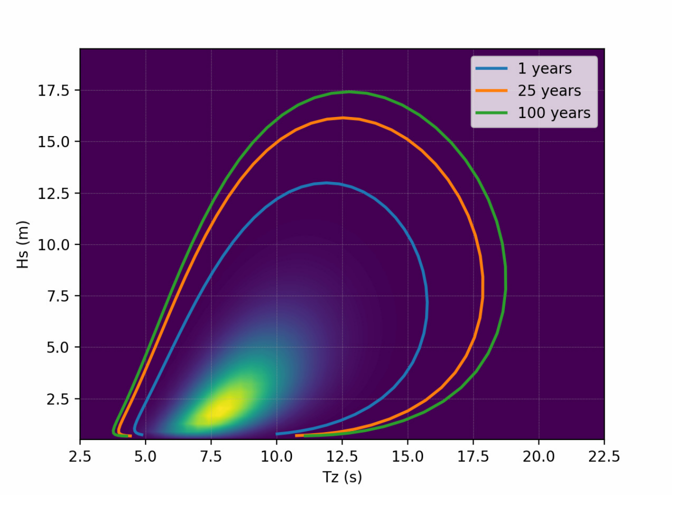
5.2.1 short-term variability

As detailed in the App 1, [2.2.1], this approach tends to underestimate the extreme response as it will neglect the short-term variability of the response. The App 1 present a method to correctly account for the short-term variability.

5.2.2 Fatigue computations

Envelope sea-states are not relevant for fatigue calculations.

Figure 5 : Examples of environmental contours (Hs,Tp)



APPENDIX 1 ENVIRONMENTAL CONTOURS

1 First Order Reliability Method (FORM)

1.1 General problem definition

1.1.1 In structural reliability problems, the computation of the multi-fold probability integral is a major issue.

Denoting $X = [X_1 ... X_n]$ the n random variables representing the uncertain quantities, the failure probability P_f is indeed formally described by the following integral:

$$P_f = Prob(g(X) \le 0) = \int_{(g(x) \le 0)} f(x) dx$$

where f(X) is the joint probability density function of X, and g(X) is the performance function defined such that g(X)≤0, the domain of integration, denotes the failure set.

This integral may be calculated by direct integration, simulation, or FORM/SORM methods, as described in this Section.

1.2 Description of FORM approach

1.2.1 As described in various papers (Y Zhao and al. 1999, Madsen & al. 1986), FORM is an analytical approximation allowing to compute the probability of exceedance of given threshold $P(Y>Y_0)$.

The FORM approach consists of projecting the input (physical) space in a standard multidimensional normal space, assuming that each uncertainty is represented using an uncorrelated normal distribution function. Indeed, thanks to the normal distribution, the probability $P(Y>Y_0)$ can be computed more easily than in the physical space, as:

$$P\{Y > Y_0\} \approx \phi(\beta)$$

The reliability index β is interpreted as the minimum distance from the origin to the limit state surface in standardized normal space and the most likely failure point is searched using mathematical programming methods.

Rosenblatt transformations are usually used to de-correlate the data (Liu and Der Kiureghian 1986).

1.3 Example of (Hs,Tz) contour

1.3.1 For a better understanding of the FORM approach, the following example is presented where we consider that the system response is supposed to depend only on two statistical parameters Hs and Tz that are described by their joint probability distribution.

Supposing a variable Y:

$$Y = function(H_s, T_z)$$

The problem is to find the probability that the variable Y exceeds a given level Y_0.

Using direct method, we need to:

- compute Y everywhere
- define the iso-response line $Y=Y_0$
- Integrate the density function in the area where $Y>Y_0$

$$P\{Y > Y_0\} = \int\int_{(Y > Y_0)} f(T_z, H_s)$$

However, this integral is difficult to solve. The FORM method can be used to simplify the calculation of this probability. The step of the method are presented hereafter:

a) H_s and T_p are transformed to uncorrelated Gaussian variables u_1 and u_2, where Φ is the standard normal distribution (see Fig 1):

$$u_1 = \Phi^{-1}(F_{Hs}(Hs))$$

$$u_2 = \Phi^{-1}(F_{Tp}(Tp|Hs))$$

$$P\{Y > Y_0\} = \int\int_{(Y > Y_0)} f(u_1, u_2)$$

b) using an optimization process under constraint, the nearest point β of the iso response $Y=Y_0$ can be found with regards to the origin (see Fig 2)

c) Iso response line is approximated by its tangent at the point where the density function is maximum, hence the safety index β defined above (see Fig 3)

d) Finally, the probability is computed thanks to the normal distribution (see Fig 4):

$$P\{Y > Y_0\} \approx \int\int_{((u_1, u_2) > \text{tangent})} f(u_1, u_2) = \Phi(\beta)$$

Figure 1 : Direct computation of $P(Y>Y_0)$

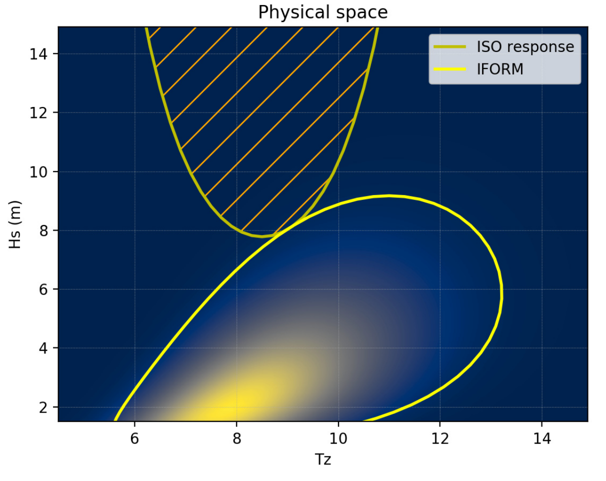


Figure 2 : (u_1,u_2) in the normal space

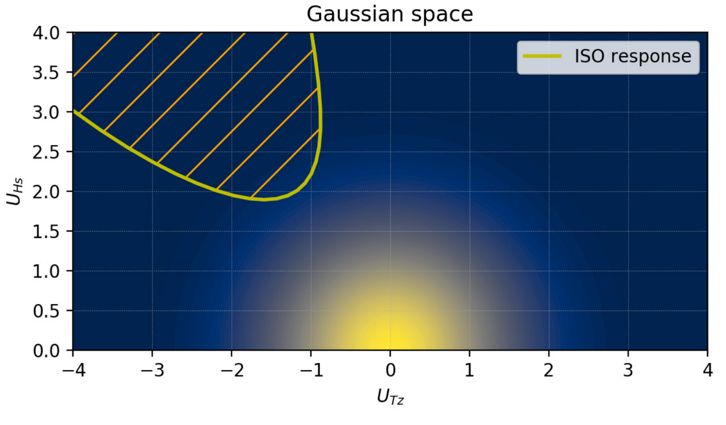


Figure 3 : Definition of the safety index β

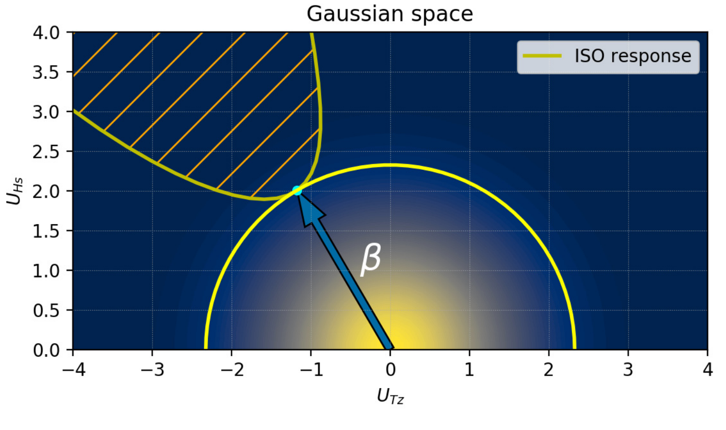
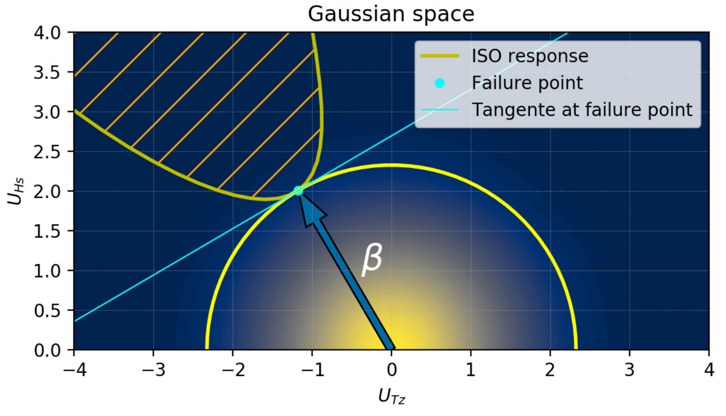


Figure 4 : Linearization of the isoline $Y=Y_0$



1.4 SORM approach

1.4.1 Because the performance function is approximated by a linear function in u-space at the design point, accuracy problems occur when the performance function is strongly non-linear in the U-space. The Second-Order Reliability Method (SORM) has been established as an attempt to improve the accuracy of FORM. SORM is obtained by approximating the limit state surface in u-space at the design point by a second-order surface.

Note 1: This method is fully described in several papers, such as Zhao & al, Structural Safety 21 (1999) 95-112, A general procedure for first/second-order reliability method (FORM/SORM).

2 Inverse FORM (I-FORM)

2.1 Description

2.1.1 General

The Inverse FORM is one of the main techniques used in the development of extreme sea-state contours. As detailed in Article [1], in the standard FORM approach, a threshold value is considered and its likelihood is estimated in the standard normal space. The I-FORM approach (Winterstein, et al. 1993) is basically the opposite approach. It starts from the normal space and a probability of occurrence (for instance a return period of 10, 50 or 100 years) that define isolines. These isolines are then transposed into the original uncertain input space in order to evaluate the potential range of extreme values.

2.1.2 Limits of FORM approach

Considering that the response Y is a deterministic function of the sea-state variable X, the uncertain quantities X are transformed from the physical space to a set of standard normal variables U, so that:

$$Y = y(U)$$

Neglecting the variability of the response, the FORM approach detailed in Article [1] will lead to the computation of the failure probability P_f, associated with exceeding a known response capacity y_{cap}. As it has been shown in [1.2], the FORM allows to estimate P_f and the associated reliability index:

$$\beta = -\Phi^{-1}(1 - P_f)$$

Knowing y_{cap}, P_f and β are found through an optimization process.

Here the design capacity y_{cap} is given and the reliability index β is calculated. However, y_{cap} is usually not know, and the reliability index β is more considered as a target value. For practical situations, the FORM method does not seem to be easily applicable.

2.1.3 I-FORM

The I-FORM method is the opposite approach, where the exceedance probability P_f, hence the minimal distance β to the failure surface (see [1.3.1]) is specified, and the design capacity is the unknown parameter.

First, the physical variables $X = [X_1 \ldots X_n]$ are transformed into independent variables $U = [u_1 \ldots u_n]$ following a standard normal distribution. Giving the exceedance probability P_f, it is possible to calculate the safety index β and to define the N dimensions sphere in the Gaussian space so that:

$$\sqrt{u_1^2 + \ldots + u_N^2} = \beta$$

The inverse transformed of the N-dimensions sphere gives the N-dimensions contour in the physical space. An example is developed in [2.2] in order to illustrate this method.

2.2 Example of (Hs,Tp) contour

2.2.1 In this example, the same as in [1.3], the variable Y corresponding to a certain probability is calculated.

The steps of the I-FORM method are explained hereafter:

a) the physical variables H_s and T_z are transformed into independent variables u_1 and u_2 following a standard normal distribution (see [1.3.1])

b) the safety index β is computed as

$$\beta = -\Phi^{-1}\left(\frac{1}{N_{ss}}\right)$$

where:

Φ : the standard normal (or Gaussian) distribution function

N_{ss} : the number of sea-states with a duration T_{ss} as $P=1/N_{ss}$ where P is the probability of exceedance

c) the circle of radius β is defined in the Gaussian space (see Fig 5)

d) the contour is computed in the Gaussian space

$$\sqrt{u_1^2 + u_2^2} = \beta$$

e) the inverse transformed of this circle gives the envelop curve in the physical space (see Fig 6).

If we define the return period T_R as:

$$N_{ss} = T_R \times 365.25 \times \frac{24}{T_{ss}}$$

With this approach the response is computed for each sea-state of the envelope curve and the maximum along the curve is supposed to correspond to the return period T_R .

It is important to note that because this approach does not take into account the short-term variability, there is no rule to select a proper characteristic value for the short-term maximum.

Figure 5 : Gaussian contour (u1, u2)

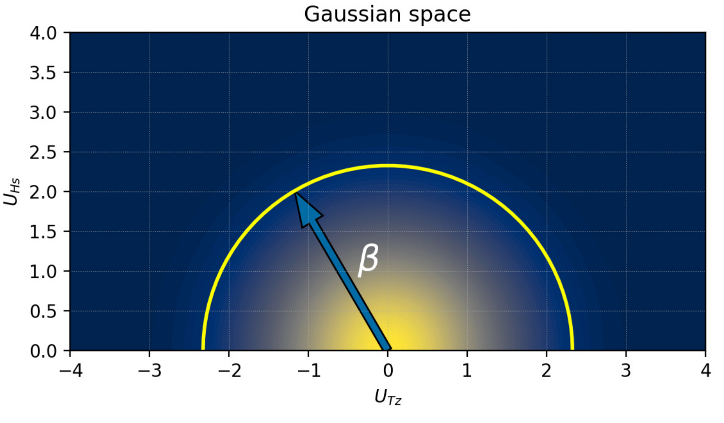
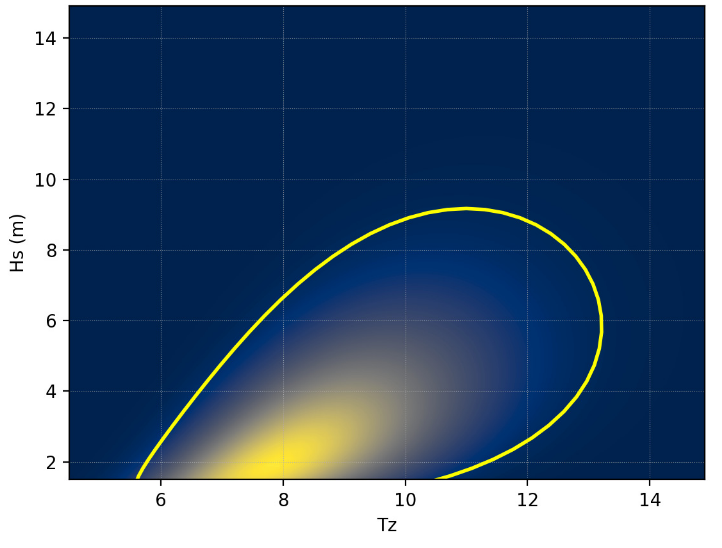


Figure 6 : Physical contour (Hs, Tp)



3 I-FORM with short-term variability of the response

3.1 Limit of I-FORM approach without short-term variability

3.1.1 As explained in [2.1.3], the I-FORM approach presented before completely neglects the short-term variability of the response Y. This was acknowledged by Winterstein et al (1993) who proposed to use an "inflated" return period (from 200 years to 1400 years) based on the FORM omission factors introduced by Madsen (1988). However, the determination of the inflated RP requires the knowledge of the relative importance of the short-term variability to the total variability of the response. This factor being case dependent, several research works have proposed other methods to account for the short-term variability.

3.2 I-FORM with short-term variability

3.2.1 Quantile of the short-term response

In order to include the short-term variability in the I-FORM approach, an additional random variable is introduced as the quantile of the short-term response Q. In Article [2], the response Y was defined as a function of the N random variables $X = [X_1 \dots X_n]$, hence:

$$Y = f(X)$$

Including the short-term variability, the response Y is know defined as function of N+1 variables, hence $X = [X_1 \dots X_n]$ and Q.

$$Y = f(X, Q)$$

Considering that the random variables can be classed in long-term variables or short-term variables, it is also possible to consider that a random maximum response on a random 3h environmental condition can then be seen as a function of the two following parameters:

- the return period of the mean response RP (how severe is the environmental condition for the response)
- the quantile Q of the 3h short-term maximum (how severe is that particular realization).

In other words, the random maximum response is a function of only two variables, one accounting for the long-term variability (RP), the other accounting for the short-term variability (Q).

The 100 years contour is defined by all the combinations of RP and short-term quantiles satisfying the following relationship, where Φ is the standard normal distribution:

$$\sqrt{{U_{LT}}^2 + {U_{ST}}^2} = \sqrt{u_1^2 + \ldots + u_n^2 + u_{n+1}^2} = \Phi^{-1}\left(1 - \frac{1}{292200}\right) \approx 4.50$$

$$RP = \frac{1}{2922(1 - \Phi(U_{LT}))}$$

$$Q = \Phi(U_{ST})$$

Using the I-FORM method, the unit response is found by computing all the points on the 100 years contour. The highest response is the I-FORM approximate of the exact 100 years response. The circular contour in the Gaussian space (β_{LT},β_{ST}) is transformed in the physical space (RP,Q) using the above equation. The contour is plotted in Fig 7.

It can be observed on the contour that the highest mean responses (corresponding to the highest RP) are to be associated with the smallest quantiles (median). In the opposite the smallest mean response (small RP) are to be associated with very large quantiles. The output of the I-FORM method is the approximated value of the 100 years response and the failure point, which is the point of the contour where the response is maximum. This failure point gives a good indication on the relative importance of the short-term and the long-term variability.

However this second method is still time consuming, as the contour has to be described by a large number of point in order to be sure not to miss the highest response. Furthermore, computing very large quantiles of the response at smaller RP requires again a very large number of simulations of the same short-term condition (see Fig 7).

Figure 7 : I-FORM contour Quantile

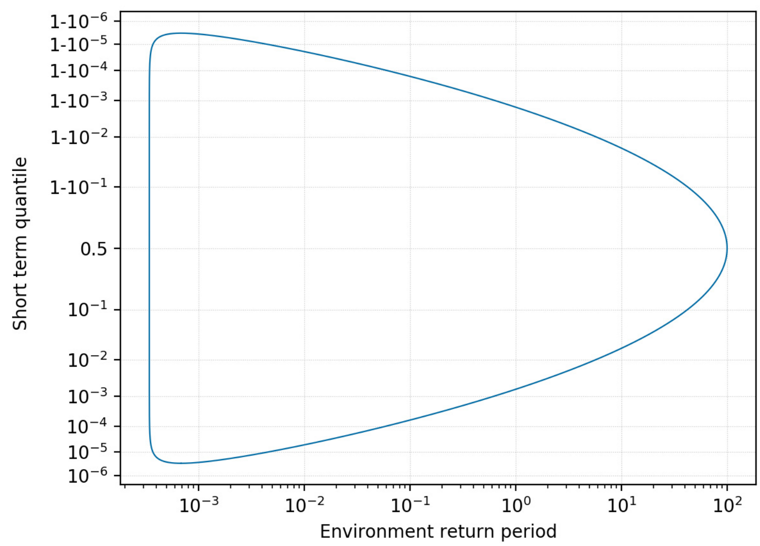
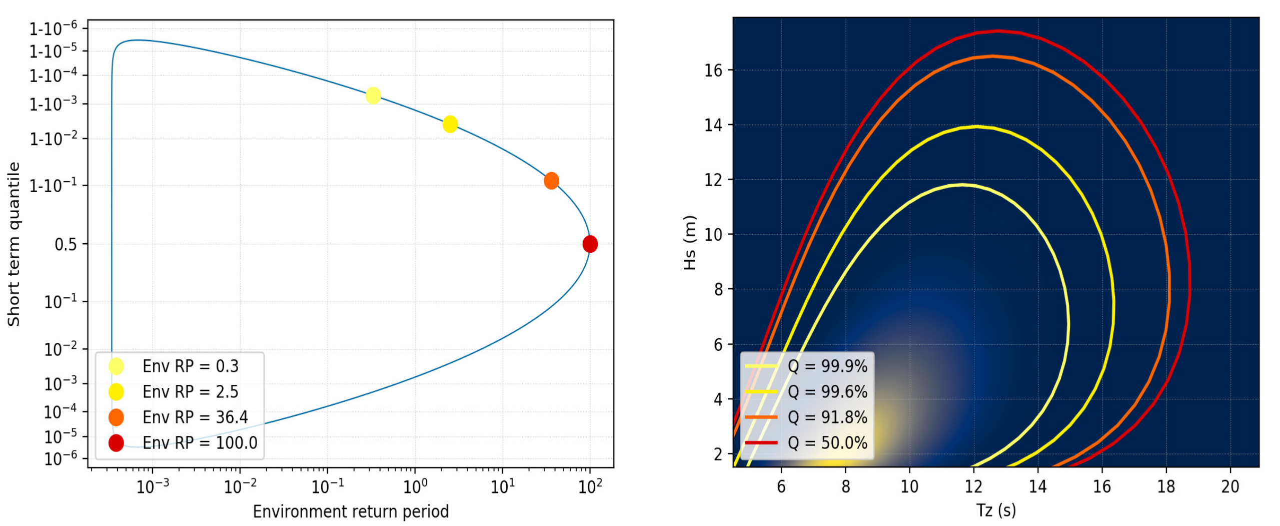


Figure 8 : Envelope curves in the physical space (Hs, Tz) taking into account the short-term variability



3.3 Example of (Hs, Tp) contour

3.3.1 I-FORM with variability of the short-term response

Going back to the (Hs, Tp) contour and to illustrate the influence of the short-term variability, the contour is computed again, including the short-term variability. The variable X is now depending on three random parameters: H_s, T_z and p the quantile of the short-term maximum.

$$X = \text{function}(H_s, T_z, p)$$

In the Gaussian space, it leads to three variables u_1, u_2 and u_3. The surface contour is computed and transformed into the physical space.

$$\Phi\left(\sqrt{u_1^2 + u_2^2 + u_3^2}\right) = \frac{1}{N_{ss}}$$

Due to this third variable u_3, the radius is now a sphere in the Gaussian space. The inverse transformed of this sphere to the physical space is a set of envelope curves corresponding to different quantiles p (see Fig 8).

APPENDIX 2 EXAMPLES OF APPLICATIONS OF LONG-TERM APPROACHES

1 General

1.1 Objectives

1.1.1 This Appendix presents several examples of possible application of long-term approaches. Examples of both multiple design sea-states (see Sec 6, [3]) and envelope sea-states applications (see Sec 6, [5]) are presented here. They are only given as typical illustration of the approaches presented in Sec 6.

1.1.2 In the Article [2], examples of computations of long-term fatigue damage and extreme structural response for a typical ship using a multiple design sea-states approach are presented.

1.1.3 In the Article [3], examples of computations of long-term extreme response of mooring line tension using envelope sea-states approach are presented.

2 Multiple design sea-states

2.1 Fatigue damage computation

2.1.1 Selection of design sea-states

As described in Sec 6, [3.1.2], the first step is to perform linear fatigue computation in order to obtain:

- fatigue damage
- azimuth contribution
- sea-states contribution.

From these first results, design headings (see Fig 2) and sea-states are selected trying to cover the most contributive conditions (see Fig 1).

Figure 1 : Examples of design headings

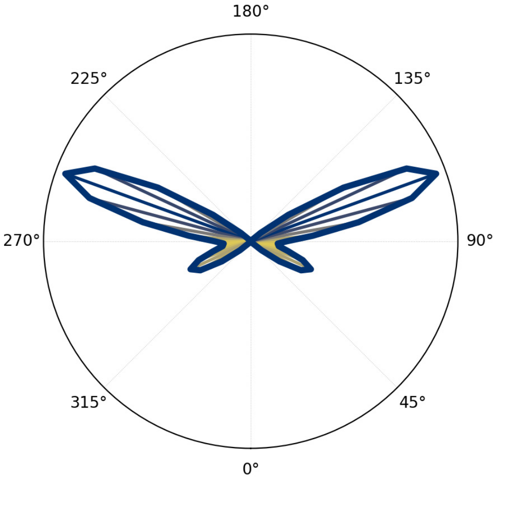
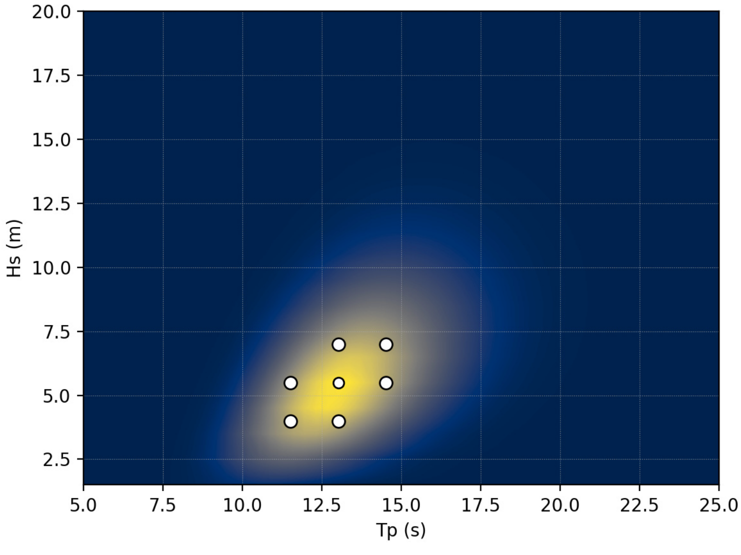


Figure 2 : Examples of design sea-states selection



2.1.2 Damage ratio and characteristic stress ratio

Short-term linear and non-linear simulations are performed on all the selected conditions, so that we get:

- linear fatigue damage D^L
- non-linear fatigue damage D^{NL}
- damage ratio and characteristic stress ratio

$$f_D^{NL}(\mu, Hs, Tp) = \frac{D^{NL}(\mu, Hs, Tp)}{D^L(\mu, Hs, Tp)}$$

$$f_\sigma^{NL}(\mu, Hs, Tp) = \sqrt[M]{\frac{D^{NL}(\mu, Hs, Tp)}{D^L(\mu, Hs, Tp)}}$$

where μ is the heading and M is the slope of the S-N curve.

2.1.3 Interpolation/extrapolation to all sea-states

For each design heading, the stress ratio is interpolated/extrapolated to all the sea-states (see Fig 3).

Then the non-linear damage can be computed for each sea-state as:

$$D^{NL}(\mu, Hs, Tp) = (f_\sigma^{NL}(\mu, Hs, Tp))^m D^L(\mu, Hs, Tp)$$

The non-linear damage is plotted in Fig 4.

At this stage, it is important to check that the fatigue damage contribution remains inside the computed sea-states with the non-linear computations. If not, the full procedure should be started again with a new selection of design sea-states.

Figure 3 : Example of stress ratio interpolation/extrapolation

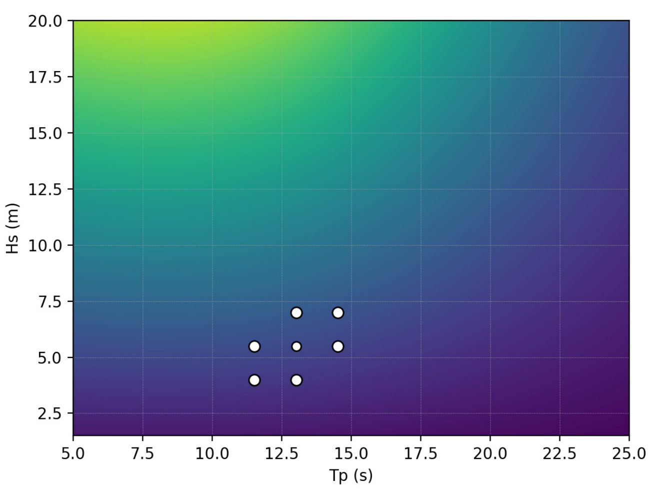
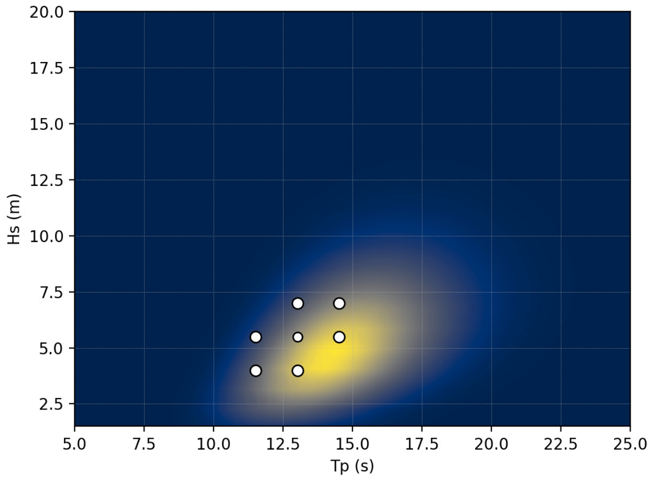


Figure 4 : Damage for all sea-state



2.1.4 Global damage ratio for each heading

For each heading μ, the total non-linear damage can then be computed from the damage of each sea-state.

$$D_\mu^{NL} = \sum_{Hs,\,Tp} \alpha(Hs, Tp) D^{NL}(\mu, Hs, Tp)$$

Then the global damage ratio and stress ratio can be computed for each heading.

$$f_D^{NL}(\mu) = \frac{D_\mu^{NL}}{D_\mu^{L}}$$

$$f_\sigma^{NL}(\mu) = \sqrt[m]{\frac{D_\mu^{NL}}{D_\mu^{L}}}$$

2.1.5 Total non-linear fatigue damage

The stress ratio is now interpolated/extrapolated to all the headings.

The total non-linear damage for each heading μ is computed:

$$D_\mu^{NL} = f_\sigma^{NL}(\mu)^m D_\mu^{NL}$$

So the total damage can be computed as:

$$D^{NL} = \sum_\mu \alpha(\mu) D_\mu^{NL}$$

Finally the global damage ratio and the characteristic ratio are computed:

$$f_D^{NL} = \frac{D^{NL}}{D^{L}}$$

$$f_\sigma^{NL} = \sqrt[m]{\frac{D^{NL}}{D^{L}}}$$

2.2 Extreme values computations

2.2.1 Selection of design sea-states

As per fatigue calculation, the first step is to perform linear extreme calculations in order to obtain:

- linear extreme single amplitude
- azimuth contribution
- sea-states contribution.

From this computations, design headings and sea-states are selected to cover the most contributive conditions to the extremes. However, these sea-states can impose very long short-term calculations duration (10, 100, 1000 hours...) in order to obtain a good convergence.

To reduce this required computation time, increased design sea-states (see Fig 5) can be defined (see the increased wave height method detailed in Sec 5, [3.3.2]). These method implies the following assumption: the non-linearity ratio is not depending on the Hs for a given target response. The validity of this assumption have been studied in different papers (see Derbanne et al. OMAE 2012).

2.2.2 Linear and non-linear distributions

short-term linear and non-linear calculations are performed on the selected design sea-states. From these computations, the coefficient of non-linearity $f_{NL}(\mu,Tp,x_{NL})$ can be derived for a range of x_{NL}:

$$f_{NL}(\mu, Tp, x_{NL}) = \frac{x_{NL}}{x_L}$$

As explained in Sec 5, [2.1], a Rayleigh distribution can be used to describe linear responses:

$$\nu_L(x_L) = \frac{1}{Tz}\exp\left(-\frac{x_L^{\ 2}}{2m_0}\right)$$

Using the calculations of f_{NL}, the non-linear distributions n_{NL} can then be derived as:

$$\nu_{NL}(x_{NL}) = \frac{1}{Tz}\exp\left(-\frac{(x_{NL}/f_{NL})^2}{2m_0}\right)$$

2.2.3 short-term exceedance rate for each heading

A value of x_{NL} is chosen. For each heading μ, the non-linear coefficient f_{NL} is interpolated to other Tp.

The short-term exceedance rate is computed for all sea-states:

$$\nu_{NL}(\mu, Hs, Tp, x_{NL}) = \frac{1}{Tz(Tp)}\exp\left(-\frac{(x_{NL}/f_{NL}(\mu, Tp, x_{NL}))^2}{2m_0(\mu, Hs, Tp)}\right)$$

2.2.4 Long Term exceedance rate for each heading

From [3.3.3], the long-term exceedance rate for each heading μ, is computed:

$$\nu_{Long-Term}(x_{NL}, \mu) = \sum_{Hs, Tp} pss(Hs, Tp)\nu_{NL}(\mu, Hs, Tp, x_{NL})$$

2.2.5 Long Term exceedance rate for all headings

f_{NL} is interpolated / extrapolated to all headings, so that the long-term exceedance rate for each all heading is computed.

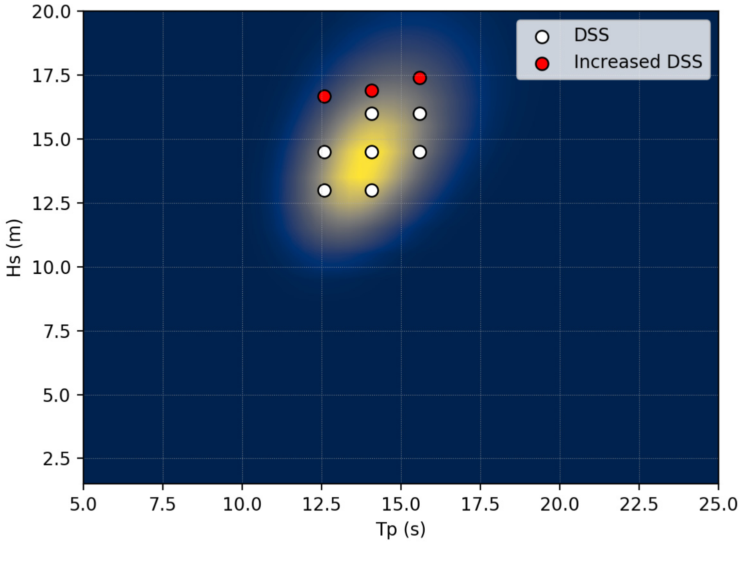
Finally the long-term exceedance rate is computed:

$$\nu_{Long-Term}(x_{NL}) = \sum_{\mu} pss(\mu)\nu_{Long-Term}(x_{NL}, \mu)$$

Numerical solvers can be then used to found x_{NL} such as:

$$\nu_{Long-Term}(x_{NL}) = 1$$

Figure 5 : Increased design sea-states



3 Envelope sea-states

3.1 2-D contour

3.1.1 The example used here to illustrate an envelope approach is a computation of mooring line tension response using only a 2D contour (Hs,Tp), see Fig 6. It has to be noted here that the effect of the other environmental parameters (wind and current) are neglected as it is just an illustration of the method presented in Sec 6, [5]. The (Hs, Tp) environmental contour is built using I-FORM approach presented in the App 1.

In theory, the computations of the tensions should be performed on each of the sea-states that form the contour, but it is possible to reduce the number of computations by taking only the largest value of the parameter. In this case, and if it is considered that the response mainly depends on Hs, only the highest value of Hs will be considered, and a sensitivity study on the period Tp will be performed with few points above the contour, as presented on Fig 7.

Figure 6 : Example of 100 years (Hs,Tp) contour

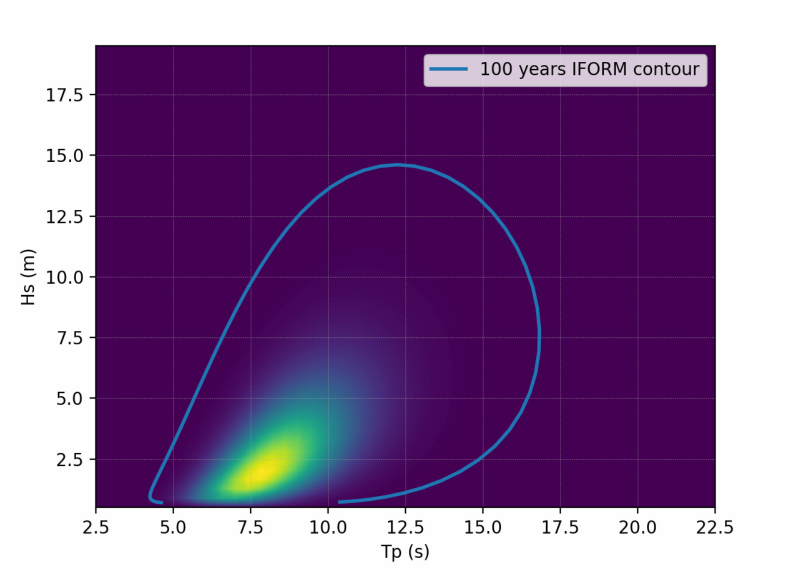


Figure 7 : Tp sensitivity study

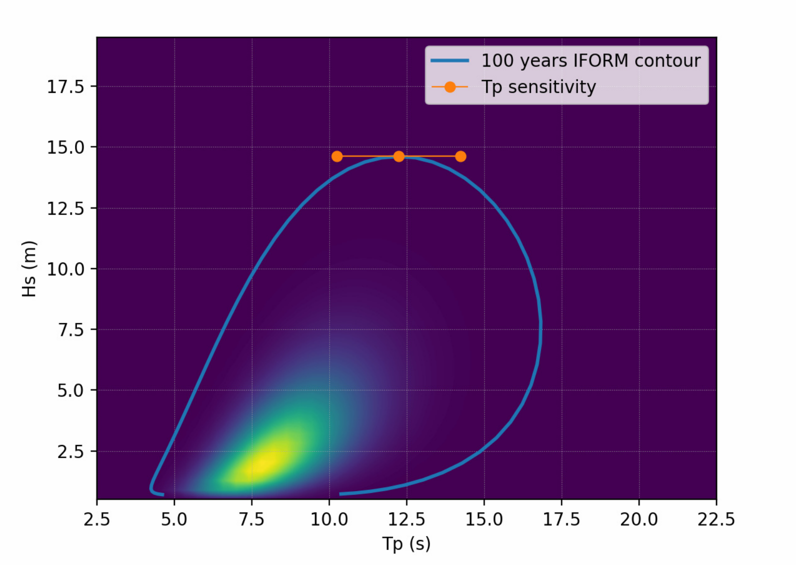
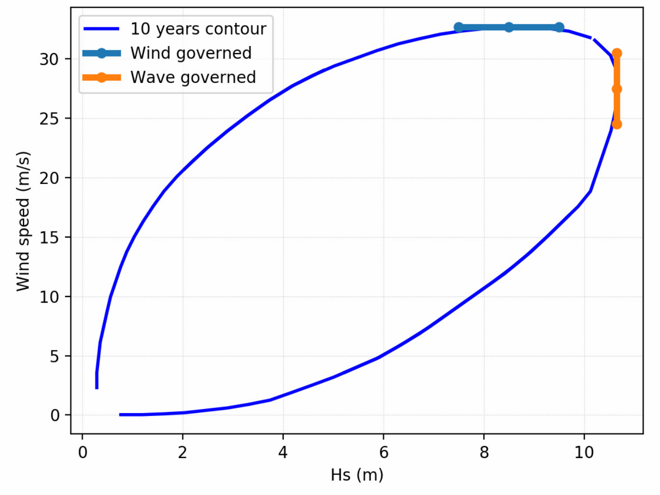


Figure 8 : (Ws, Hs) contour



3.2 N-dimensions contour

3.2.1 In the design process of offshore mooring system, the waves are usually not the only environmental parameter to be considered. Wind and current loads also have a large influence on the design, and they cannot considered as independent parameters. A good possible representation of the environment could be a N dimensions contour taking into account several parameters such as Hs, Tp, wind speed, current speed and all the possible directions of waves, wind and current. However, due to the high complexity of such contours, for both generation and use, the current industry practice is to use what could be called the "corners" of these contours. The main idea, as it has been developed for the (Hs,Tp) contour in [3.1.1], is to take the maximum value of one parameters and some associated relatively high value for the remaining parameters. Using this approach, we limit the number of computations.

On the Fig 8, we can see a 2D view of the N-dimensions contour where only the wind speed Ws and Hs are represented (the other parameters are considered fixed). Here, the maximum Hs is considered (wave governed), and associated Ws are considered to composed the sea-states that are to be computed. The same approach should also be performed with associated current speed Cs and all the other parameters composing the N-dimensions contour. As such contours are not often available, metocean reports usually directly give the associated return period, or even directly the intensity values to considered. Rules, such as NR493, Appendix 2, also propose some methods to correctly account for each governing parameter and its associated parameters.

3.3 Estimation of short-term maximum

3.3.1 The main standards of the offshore industry impose for the design of permanent mooring system to perform time domain calculations in order to account for all the non-linearities. Thanks to the contour method, few worst (Hs, Tp) conditions have been selected and the simulations are performed on those sea-states. Several methods exist to estimate the maximum tension Tmax to be considered for the design, but it is chosen here to used the method presented in Sec 5, [3.5.4] with a 90% quantile estimation in order to correctly account for the short-term variability.

Computing time constraints impose to evaluate Q_{90} from a limited number of N simulations. Because N is usually small (at least 5), the estimation est(Q_{90}) of the quantile Q_{90} may not be accurate. However this estimation is corrected to ensure that the final estimation will be at least equal to the target value with a level of confidence of 90%. On the basis of the following formulation:

$$\mathrm{est}(T_{max}) = \mathrm{est}(Q_{90}) + \frac{\alpha}{\sqrt{N}}\mathrm{est}(\sigma)$$

where σ is the standard deviation, α is function of N (given in Sec 5, Tab 1), and est(X) is the estimation of the variable X from the N simulations results.

It is also to be noted that the values of α have been derived assuming that P_{max} follows a Gumbel distribution, and targeting a 90% level of confidence, hence:

$$P\left(\mathrm{est}(Q_{90}) + \frac{\alpha}{\sqrt{N}}\mathrm{est}(\sigma) > Q_{90}\right) = 0.9$$

Depending on the available metocean data, several different directions have to be checked, and the maximum tension T_{max} is taken as the design tension.

APPENDIX 3 STRATEGIES FOR THE DETERMINATION OF EXTREME RESPONSE / FATIGUE DAMAGE

1 General

1.1 Scope and applications

1.1.1 In this Article, the different approaches developed previously are applied to some real industrial applications (loads and response calculations). The main purpose of this section is to list and sum up the different strategies that are available for the computation of long-term extreme response/fatigue damage, with sufficient accuracy and reasonable computation time.

Strategies for the determination of extreme response are listed in Article [2]:

- for a linear long-term extreme response, see [2.2]
- for a linear long-term extreme response with a non-linear correction based on design wave, see [2.3]
- for a linear long-term extreme response with a non-linear correction based on a single design sea-state, see [2.4]
- for a short-term approach of extreme response based on envelope sea-states, see [2.5]
- for a linear long-term extreme response with a non-linear correction based on multiple design sea-states, see [2.6]
- for a linear long-term extreme response with a non-linear correction based on multiple design sea-states using EDWs, see [2.7]
- for a prescriptive approach of extreme response, see [2.8].

Strategies for the determination of fatigue damage are listed in Article [3]:

- for linear spectral fatigue damage, see [3.1]
- for linear spectral fatigue damage with non-linear correction based on a single design sea-state, see [3.2]
- for linear spectral fatigue damage with non-linear corrections based on multiple design sea-states, see [3.3]
- for linear spectral fatigue damage corrected by several stress based design waves, see [3.4]
- for fatigue damage from load based design waves at several probability levels, see [3.5]
- for fatigue damage from load based design waves at one probability level, see [3.6]
- for a prescriptive approach of fatigue damage, see [3.7].

1.2 Table

1.2.1 In order to simplify the description of the different strategies, a table (see Tab 1) presenting the different step of the strategy has been built. In column the different long-term approaches are presented: envelop sea-states, single sea-state, Multiple design sea-state, or linear spectral approach (all these approaches are presented in Sec 6).

In line, two short-term approaches are proposed: either sea-state short-term approach or EDW. The sea-state short-term approach gathers the different short-term approaches presented in Sec 5, [2] and Sec 5, [3], and the EDW approach gathers the different approaches defined in Sec 5, [4]. The choice of the method is to be made depending on the project constraints (available computing time, type of project, etc.)

When needed, the order of the different steps of the strategy will be given in the table.

Table 1 : Typical table used in this appendix

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state		
Multiple design sea-states		
Entire scatter diagram		

2 Strategies for the determination of extreme response

2.1 Types of response

2.1.1 The response can be either loads or stress (yielding or buckling for instance).

2.2 Linear long-term extreme

2.2.1 The computations of RAOs give the short-term distributions $P_i(x)$ for all the scatter diagram (as detailed in Sec 5, [2]). The long-term response X associated to a risk α and a return period RP can be directly computed from the $P_i(x)$, as explained in Sec 6, [2].

Table 2 : Linear long-term extreme

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state		
Multiple design sea-states		
Entire scatter diagram	①Linear loads or stress	

2.3 Linear long-term extreme + non-linear correction based on design wave

2.3.1 A first round of linear computations allows to identify the most contributive sea-state, hence the design sea-state (as detailed in Sec 6, [4]). A design wave (see definition in Sec 5, [4]) targeting the linear long-term value is identified. If an irregular design wave is used (see Sec 5, [4.3]), its parameters are to be defined according to the design sea-state parameters.

The non-linear response is computed on the design wave. This non-linear extreme is the long-term non-linear extreme.

2.3.2 If the extreme stress is needed, the same method is applied with several carefully chosen governing parameters (loads or stress). The stress response is then computed on the selected design waves, and the highest stress response corresponds to the long-term response X associated to a risk α and a return period RP.

Table 3 : Linear long-term extreme + non-linear correction based on design wave

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state		②Non-linear loads and stress
Multiple design sea-states		
Entire scatter diagram	①Linear loads or stress	

2.4 Linear long-term extreme + non-linear correction based on a single design sea-state (+ design wave for stress)

2.4.1 A first round of linear computations allows to identify the most contributive sea-state, hence the design sea-state (as detailed in Sec 6, [4]). The return period of the linear load extreme on the selected sea-states is calculated (it usually corresponds to several hours), and a time-domain computation is performed on this design sea-state to evaluate the non-linear extreme at the same return period. As it is usually a very long simulation, extrapolation methods or increased design sea-state approach (see Sec 5, [3.3]) can be used to reduce computing time.

This non-linear extreme is the long-term non-linear extreme.

2.4.2 If extreme stress is needed, the design wave (see definition in Sec 5, [4]) leading to the same non-linear load response is identified, and the structural response is computed on this EDW.

Table 4 : Linear long-term extreme + non-linear correction based on single design sea sate (+design wave)

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state	②Non-linear loads	③Stress
Multiple design sea-states		
Entire scatter diagram	①Linear loads	

2.5 Short-term approach based on envelope sea-states

2.5.1 Envelope sea-states corresponding to a given RP and a given T_{ss} are defined using I-FORM approach (see App 1 for more details in the formation of such environmental contours). For each sea-state composing the environmental contour, multiple short-term simulations of T_{ss} hours are performed. As it is shown in the example presented in the App 2, [3], only few sea-states inflating the contour (hence adding sea-states for sensitivity) may be considered to reduce the computing time with consideration for the different parameters.

For each sea-state, a certain characteristic value (MPM, median or higher quantile) is evaluated from the repeated simulations. It has to be noted here, that special care is to be given to the convergence of this estimation, in particular if the number of repeated simulations is low.

Finally, the highest response over the contour is the long-term extreme response.

2.5.2 If the extreme stress is needed, the design wave (see definition in Sec 5, [4]) leading to the same non-linear load response is identified, and the structural response is identified on this EDW.

Table 5 : Short-term approach based on envelope sea-states

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state	①Non-linear loads	
Single design sea-state		②stress
Multiple design sea-states		
Entire scatter diagram		

2.6 Linear long-term extreme + non-linear correction based on multiple design sea-states (+ design wave for stress)

2.6.1 A first round of linear computations allows to identify the most contributive sea-states, hence the design sea-states (see Sec 6, [3]). Time domain non-linear computation on each design sea-states gives the correction to be applied (interpolated/extrapolated) to all the other sea-states. Knowing the corrected short-term distribution $P_i(x)$, the long-term response can be computed.

It is to be noted that iterations may be necessary. Indeed, it has to be checked that the most contributive conditions are inside the chosen conditions. If not, new sea-states/headings are chosen and the process is started again.

2.6.2 If the extreme stress is needed, the design wave (see definition in Sec 5, [4]) leading to the same non-linear load response is identified, and the structural responses is computed on this EDW.

Table 6 : Linear long-term extreme + non-linear correction based on multiple design sea-states (+ design wave for stress)

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state		③Stress
Multiple design sea-states	②Non-linear loads	
Entire scatter diagram	①Linear loads	

2.7 Linear long-term extreme + non-linear correction based on multiple design sea-states using EDWs (+ design wave for stress)

2.7.1 A first round of linear computations allows to identify the most contributive sea-states, hence the design sea-states (see Sec 6, [3]). Using a small number of design waves (see definition in Sec 5, [4]), non-linear computations are performed and the correction is applied (interpolated/extrapolated) to all the other sea-states. Knowing the corrected short-term distribution $P_i(x)$, the long-term response can be computed.

It is to be noted that the iterations may be necessary. Indeed, it has to be checked that the most contributive conditions are inside the chosen conditions. If not, new sea-states/headings are chosen and the process is started again.

2.7.2 If the extreme stress is needed, the design wave leading to the same non-linear load response is identified, and the structural responses is computed on this EDW.

Table 7 : Linear long-term extreme + non-linear correction based on multiple design sea-states using EDWs (+ design wave for stress)

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state		③Stress
Multiple design sea-states		②Non-linear loads
Entire scatter diagram	①Linear loads	

2.8 Prescriptive approach

2.8.1 In this approach, the load cases are directly defined by rules and based on EDW (see definition in Sec 5, [4]) for a given RP (25 years in BV Rules for Classification of Steel Ships). The stress response is computed from each load case, and the maximum stress is found over all the design waves. Typical application of the prescriptive approach are the yielding and buckling checks imposed by rules and standards.

Table 8 : Prescriptive approach

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state		①Stress
Multiple design sea-states		
Entire scatter diagram		

3 Strategies for the determination of fatigue damage

3.1 Linear spectral fatigue damage

3.1.1 The computations of RAOs give the short-term distributions of stress cycle $f(\Delta\sigma)$ for all the sea-states of the scatter diagram. The long-term distribution of response cycles can then be directed computed to get the long-term linear fatigue damage (see Sec 6, [2]).

Table 9 : Linear spectral fatigue damage

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state		
Multiple design sea-states		
Entire scatter diagram	①Linear stress	

3.2 Linear spectral fatigue damage + non-linear correction based on a single design sea-state

3.2.1 Linear computations give the short-term distributions of stress cycle $f(\Delta\sigma)$ and to compute the short-term linear damage of each sea-state (see Sec 4, [2.2.2]) and the long-term linear damage (see Sec 4, [4.2.2]). The most contributive sea-state is identified, and a long time-domain simulation (usually 3 hours) is performed on these design sea-state, with a special attention on the convergence of the hourly damage.

The short-term linear damage D_L on this design sea-state is computed using closed form expression and the non-linear damage D_{NL} using rainflow counting method (see Sec 5, [3.6]). Finally the non-linear correction factor is computed as D_{NL}/D_L and is applied to the long-term linear damage to get the long-term non-linear damage.

Table 10 : Linear spectral fatigue damage + non-linear correction based on a single design sea-state

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state	②Non-linear stress	
Multiple design sea-states		
Entire scatter diagram	①Linear stress	

3.3 Linear spectral fatigue damage + non-linear corrections based on multiple design sea-states

3.3.1 Linear computations give the short-term distributions of stress cycle f(Δσ) and to compute the short-term linear damage of each sea-state (see Sec 4, [2.2.2]) and the long-term linear damage (see Sec 4, [4.2.2]. The most contributive sea-states are identified, and long time-domain simulations (usually 3 hours) are performed on these design sea-state, with special attention on the convergence of the hourly damage. The short-term linear damages Di_L on these design sea-states are computed using closed form expression and the non-linear damages Di_{NL} using rainflow counting method (see Sec 5, [3.6]). Non-linear correction factors are then computed as Di_{NL}/Di_L and are interpolated/extrapolated to other sea-states to get the non-linear damage for all the sea-states. Finally, the long-term non-linear damage is obtained by long-term summation of the short-term non-linear damages.

Table 11 : Linear spectral fatigue damage + non-linear corrections based on multiple design sea-states

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state		
Multiple design sea-states	②Non-linear stress	
Entire scatter diagram	①Linear stress	

3.4 Linear spectral fatigue damage corrected by several stress based design waves

3.4.1 First, a linear long-term approach is performed to get the long-term stress distribution. For each probability level (usually from 10^{-1} to 10^{-6}), the design sea-state is defined as the most contributive sea-state (see Sec 6, [4]), and a design wave (preferably an irregular design wave) is defined using the design sea-state characteristics and targeting the long-term stress range at the probability level (see Sec 5, [4] for definition of design waves).

Then, the non-linear stress range is computed with this design wave (two design waves have to be applied: one for the maximum and one for the minimum). The non-linear long-term stress distribution is computed, and the non-linear long-term fatigue damage is finally computed.

Table 12 : Linear spectral fatigue damage corrected by several stress based design waves

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state		②Non-linear stress
Multiple design sea-states		
Entire scatter diagram	①Linear stress	

3.5 Fatigue damage from load based design waves at several probability levels

3.5.1 Previously to the calculations, linear dominant load parameters are identified. A linear long-term approach give the long-term loads distributions. The design sea-state is defined as the most contributive sea-state (see Sec 6, [4]) and design waves (see Sec 5, [4]) are determined (two waves per load). The stress range is computed from each design wave, and the maximum stress range over all the design waves is selected. The long-term stress range distribution is build and the long-term fatigue damage is then computed.

The NI 611 Guideline for Fatigue Assessment of Steel Ships and Offshore Units describes in details this approach.

Table 13 : Fatigue damage from load based design waves at several probability levels

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state		②Non-linear loads and stress
Multiple design sea-states		
Entire scatter diagram	①Linear loads	

3.6 Fatigue damage from load based design waves at one probability level

3.6.1 Previously to the calculations, linear dominant load parameters are identified. A linear long-term approach gives the long-term loads distributions. The design sea-state is defined as the most contributive seas state (see Sec 6, [4]) and design waves (see Sec 5, [4]) are determined (two waves per load). The stress range is computed from each design wave, and the maximum stress range over all the design waves is selected. The long-term stress range distribution is build using a Weibull distribution and the long-term fatigue damage is then computed.

The NI 611 Guideline for Fatigue Assessment of Steel Ships and Offshore Units describes in details this approach.

Table 14 : Fatigue damage from load based design waves at one probability level

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state		②Non-linear loads and stress
Multiple design sea-states		
Entire scatter diagram	①Linear loads	

3.7 Prescriptive approach

3.7.1 The load cases are defined by the rules, based on EDWs at 10^{-2} probability level. Stress range is computed from each load case, and the maximum stress range over all the design waves is selected. The long-term stress range distribution is built using a Weibull distribution with a shape factor equal to 1. Finally, the long-term fatigue damage is computed.

Table 15 : Prescriptive approach

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state		①Stress
Multiple design sea-states		
Entire scatter diagram		

Move Forward with Confidence

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