Design Sloshing Loads for LNG Membrane Tanks

May 2011

Guidance Note
NI 554 DT R00 E

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MARINE DIVISION
GENERAL CONDITIONS

ARTICLE 1

1.1. - BUREAU VERITAS is a Society the purpose of whose Marine Division (the "Society") is the classification (" Classification ") of any ship or vessel or structure of any type or part of it or system therein collectively hereinafter referred to as a "Unit" 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.

The Society:

- prepares and publishes Rules for classification, Guidance Notes and other documents ("Rules");
- issues Certificates, Attestations and Reports following its interventions ("Certificates");
- publishes Registers.

1.2. - The Society also participates in the application of National and International Regulations or Standards, in particular by delegation from different Governments. Those activities are hereafter collectively referred to as " Certification ".

1.3. - The Society can also provide services related to Classification and Certification such as ship and company safety management certification; ship and port security certification, training activities; all activities and duties incidental thereto such as documentation on any supporting means, software, instrumentation, measurements, tests and trials on board.

1.4. - The interventions mentioned in 1.1., 1.2. and 1.3. are referred to as " Services ". The party and/or its representative requesting the services is hereinafter referred to as the " Client ". **The Services are prepared and carried out on the assumption that the Clients are aware of the International Maritime and/or Offshore Industry (the "Industry") practices.**

1.5. - The Society is neither and may not be considered as an Underwriter, Broker in ship's sale or chartering, Expert in Unit's valuation, Consulting Engineer, Controller, Naval Architect, Manufacturer, Shipbuilder, Repair yard, Charterer or Shipowner who are not relieved of any of their expressed or implied obligations by the interventions of the Society.

ARTICLE 2

2.1. - Classification is the appraisement given by the Society for its Client, at a certain date, following surveys by its Surveyors along the lines specified in Articles 3 and 4 hereafter on the level of compliance of a Unit to its Rules or part of them. This appraisement is represented by a class entered on the Certificates and periodically transcribed in the Society's Register.

2.2. - Certification is carried out by the Society along the same lines as set out in Articles 3 and 4 hereafter and with reference to the applicable National and International Regulations or Standards.

2.3. - **It is incumbent upon the Client to maintain the condition of the Unit after surveys, to present the Unit for surveys and to inform the Society without delay of circumstances which may affect the given appraisement or cause to modify its scope.**

2.4. - The Client is to give to the Society all access and information necessary for the safe and efficient performance of the requested Services. The Client is 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.

ARTICLE 3

3.1. - **The Rules, procedures and instructions of the Society take into account at the date of their preparation the state of currently available and proven technical knowledge of the Industry. They 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.**

Committees consisting of personalities from the Industry contribute to the development of those documents.

3.2. - The Society only is qualified to apply its Rules and to interpret them. Any reference to them has no effect unless it involves the Society's intervention.

3.3. - The Services of the Society are carried out by professional Surveyors according to the applicable Rules and to the Code of Ethics of the Society. Surveyors have authority to decide locally on matters related to classification and certification of the Units, unless the Rules provide otherwise.

3.4. - **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.**

ARTICLE 4

4.1. - The Society, acting by reference to its Rules:

- reviews the construction arrangements of the Units as shown on the documents presented by the Client;
- conducts surveys at the place of their construction;
- classes Units and enters their class in its Register;
- surveys periodically the Units in service to note that the requirements for the maintenance of class are met.

The Client is to inform the Society without delay of circumstances which may cause the date or the extent of the surveys to be changed.

ARTICLE 5

5.1. - The Society acts as a provider of services. This cannot be construed as an obligation bearing on the Society to obtain a result or as a warranty.

5.2. - The certificates issued by the Society pursuant to 5.1. here above are a statement on the level of compliance of the Unit to its Rules or to the documents of reference for the Services provided for.

In particular, the Society does not engage in any work relating to the design, building, production or repair checks, neither in the operation of the Units or in their trade, neither in any advisory services, and cannot be held liable on those accounts. Its certificates 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.

5.3. - The Society does not declare the acceptance or commissioning of a Unit, nor of its construction in conformity with its design, that being the exclusive responsibility of its owner or builder, respectively.

5.4. - The Services of the Society cannot create any obligation bearing on the Society or constitute any warranty of proper operation, beyond any representation set forth in the Rules, of any Unit, equipment or machinery, computer software of any sort or other comparable concepts that has been subject to any survey by the Society.

ARTICLE 6

6.1. - The Society accepts no responsibility for the use of information related to its Services which was not provided for the purpose by the Society or with its assistance.

6.2. - If the Services of the Society cause to the Client a damage which is proved to be the direct and reasonably foreseeable consequence of an error or omission of the Society, its liability towards the Client is limited to ten times the amount of fee paid for the Service having caused the damage, provided however that this limit shall be subject to a minimum of eight thousand (8,000) Euro, and to a maximum which is the greater of eight hundred thousand (800,000) Euro and one and a half times the above mentioned fee.

The Society bears no liability for indirect or consequential loss such as e.g. loss of revenue, loss of profit, loss of production, loss relative to other contracts and indemnities for termination of other agreements.

6.3. - All claims are to be presented to the Society in writing within three months of the date when the Services were supplied or (if later) the date when the events which are relied on of were first known to the Client, and any claim which is not so presented shall be deemed waived and absolutely barred. Time is to be interrupted thereafter with the same periodicity.

ARTICLE 7

7.1. - Requests for Services are to be in writing.

7.2. - **Either the Client or the Society can terminate as of right the requested Services after giving the other party thirty days' written notice, for convenience, and without prejudice to the provisions in Article 8 hereunder.**

7.3. - The class granted to the concerned Units and the previously issued certificates remain valid until the date of effect of the notice issued according to 7.2. here above subject to compliance with 2.3. here above and Article 8 hereunder.

7.4. - The contract for classification and/or certification of a Unit cannot be transferred neither assigned.

ARTICLE 8

8.1. - The Services of the Society, whether completed or not, involve, for the part carried out, the payment of fee upon receipt of the invoice and the reimbursement of the expenses incurred.

8.2. Overdue amounts are increased as of right by interest in accordance with the applicable legislation.

8.3. - The class of a Unit may be suspended in the event of non-payment of fee after a first unfruitful notification to pay.

ARTICLE 9

9.1. - The documents and data provided to or prepared by the Society for its Services, and the information available to the Society, are treated as confidential. However:

- clients have access to the data they have provided to the Society and, during the period of classification of the Unit for them, to the **classification file** consisting of survey reports and certificates which have been prepared at any time by the Society for the classification of the Unit;
- copy of the documents made available for the classification of the Unit and of available survey reports can be handed over to another Classification Society, where appropriate, in case of the Unit's transfer of class;
- the data relative to the evolution of the Register, to the class suspension and to the survey status of the Units, as well as general technical information related to hull and equipment damages, are passed on to IACS (International Association of Classification Societies) according to the association working rules;
- the certificates, documents and information relative to the Units classed with the Society may be reviewed during certificating bodies audits and are disclosed upon order of the concerned governmental or inter-governmental authorities or of a Court having jurisdiction.

The documents and data are subject to a file management plan.

ARTICLE 10

10.1. - Any delay or shortcoming in the performance of its Services by the Society arising from an event not reasonably foreseeable by or beyond the control of the Society shall be deemed not to be a breach of contract.

ARTICLE 11

11.1. - In case of diverging opinions during surveys between the Client and the Society's surveyor, the Society may designate another of its surveyors at the request of the Client.

11.2. - Disagreements of a technical nature between the Client and the Society can be submitted by the Society to the advice of its Marine Advisory Committee.

ARTICLE 12

12.1. - Disputes over the Services carried out by delegation of Governments are assessed within the framework of the applicable agreements with the States, international Conventions and national rules.

12.2. - Disputes arising out of the payment of the Society's invoices by the Client are submitted to the Court of Nanterre, France.

12.3. - **Other disputes over the present General Conditions or over the Services of the Society are exclusively submitted to arbitration, by three arbitrators, in London according to the Arbitration Act 1996 or any statutory modification or re-enactment thereof. The contract between the Society and the Client shall be governed by English law.**

ARTICLE 13

13.1. - **These General Conditions constitute the sole contractual obligations binding together the Society and the Client, to the exclusion of all other representation, statements, terms, conditions whether express or implied. They may be varied in writing by mutual agreement.**

13.2. - The invalidity of one or more stipulations of the present General Conditions does not affect the validity of the remaining provisions.

13.3. - The definitions herein take precedence over any definitions serving the same purpose which may appear in other documents issued by the Society.

BV Mod. Ad. ME 545 k - 17 December 2008

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1. General

1.1 Application

The present Guidance Note provides requirements for the calculation of design sloshing loads in a cargo membrane tank containing Liquefied Natural Gas (LNG).

The present Guidance Note:

- should apply to Liquefied Natural Gas Carriers (LNGC) and offshore liquefied natural gas floating units (offshore LNG floating units) using the membrane technology
- focuses on the determination of the design sloshing loads to be applied on the Cargo Containment System (CCS) and the Inner Hull Structure (IHS)

The strength assessment of the CCS and IHS is described in the separate Guidance Note NI564 “Strength Assessment of LNG Membrane Tanks under Sloshing Loads”.

This Guidance Note proposes only a method and gives the corresponding recommendations on the procedure to be applied. It is the designer’s responsibility to opt either to use the methodology proposed in this guidance note, or to propose any other procedure. In any case, this choice should be discussed with the Society.

1.2 Notation

Based on the present Guidance Note, the additional service feature SLOSHING may be assigned to offshore liquefied natural gas floating units covered by NR542 “Rules for the Classification of Offshore Floating Gas Units”, when the sloshing loads in cargo tanks of the unit are assessed through direct calculations.

1.3 Required data

This sub-article details the data to be collected in order to determine the design sloshing loads to be applied on the CCS and the IHS.

1.3.1 Required data for seakeeping analysis and CFD calculations

The following data are required in order to perform the seakeeping analysis and Computational Fluid Dynamic (CFD) calculations:

- body plan and offsets including length between aft and forward perpendiculars, width and drafts at given loading conditions, displacement and block coefficient
- ship’s inertia described by the coordinates of the center of gravity and gyration radii at given loading conditions
- hydrodynamic input:
  - water depth
  - ship’s hull speed
- environmental conditions:
  - wave headings
  - wave spectrum forms (Pierson-Moskowitz, JONSWAP, Gauss or a given function of wave frequency)
  - wave scatter diagram
- mooring stiffness (if necessary), presence of quay and/or other nearby floating bodies
- tank arrangement and dimensions on primary barrier
- density and viscosity of LNG
- operability scenario for the LNGC or the offshore LNG floating unit:
  - tank fillings to be tested
  - filling probability
  - heading repartition
  - the area limitation where sloshing is considered not to occur
  - design return period

1.3.2 Required data for sloshing model tests review

In addition to the above mentioned data, the following ones are required in order to perform the sloshing model tests review:

- model test facility features: degrees of freedom and capacity of motion generator
- model scale
- tank model material and geometry
- liquid and ullage gas characteristics
- data acquisition system; sampling rate
- specification, location and arrangements of pressure sensors
- description of data analysis:
  - threshold
  - filtering
  - statistical fitting distribution used for the statistical post-processing
  - test of goodness of fits

1.4 Expected results

This sub-article details the expected results of the design sloshing loads assessment.

1.4.1 Seakeeping analysis results

The objective of the seakeeping analysis is to determine the sloshing excitation for the CFD calculations and the sloshing model tests. For each considered loading case, following results are expected after seakeeping analysis:

- added mass matrix (in case of wave heading analysis)
- first order motions Response Amplitude Operators (RAO) for each of the 6 degrees of freedom
- Quadratic Transfer Functions (QTF) (in case of wave heading analysis)
- short term spectral calculations for each navigation condition.

1.4.2 CFD calculations results

For each tested case, the expected results of the CFD calculations are:

- the case description (loading condition, tank, filling level, sailing condition description)
- maximum normal fluid impact velocities for an independent review of sloshing model tests
- quasi-static pressures for the IHS strength assessment
- fluid velocities and accelerations at the pump mast location for its strength assessment.

1.4.3 Sloshing model tests results

For each tested case, the expected results of the sloshing model tests review are:

- the case description (loading condition, tank, filling level, sailing condition description)
- peak files for all loaded areas of each tested case
- statistical fitting distribution used for the statistical post-processing
- short term Exceedance Probability Function (EPF) for all loaded areas of each tested case
- the bounds of the confidence intervals for the desired confidence level (to be discussed with the Society) for all loaded areas of each tested case.

Based on above data and the operability scenario, the expected results of the long term approach are:

- the long term EPF for all loaded areas of each considered operating scenario
- the bounds of the confidence intervals for the desired confidence level (to be agreed with the Society) associated with the long term EPF for all loaded areas of each operating scenario.

1.5 Symbols and abbreviations

The main symbols used in this Guidance Note are as follows:

H	Internal height of the tank between the primary membrane surfaces
H_s	Significant wave height
L	Internal length of the tank between the primary membrane surfaces
P_{3hr}	Probable 3-hour maximum statistical pressure
T_p	Peak period
T_z	Zero-up crossing period
V	Ship's hull speed
V_{max}	Ship's hull design speed
$V_{1/2}$	Ship's hull half speed

The following abbreviations are used throughout this Guidance Note:

CCS	Cargo Containment System
CFD	Computational Fluid Dynamics
EPF	Exceedance Probability Function
FLNG	LNG-FPSO
FPSO	Floating Production Storage and Offloading unit
FSRU	Floating Storage and Regasification Unit
GTT	Gas Transport and Technigaz
IACS	International Association of Classification Societies
IHS	Inner Hull Structure
LNG	Liquefied Natural Gas
LNGC	Liquefied Natural Gas Carriers
LNGRV	Liquefied Natural Gas Regasification Vessel
RAO	Response Amplitude Operator
QTF	Quadratic Transfer Functions

2. Overall methodology

2.1 Context

The importance of the sloshing loading was re-actualized in the last decade due to the increased activities in the LNG transport. Large numbers of LNGC were built or are under construction with the capacities which almost doubled as compared to the classical LNG Ships (from 138 000 m^3 to 266 000 m^3). The most common LNG ships belong to the so called membrane type and typical example is shown in Fig 1. Within the membrane type concept, which is of main concern here, the LNG is kept liquid at very low temperature (-160℃) by complex insulation system which is attached to the ship structure.

At the same time as the size of LNG vessels increased, the operational requirements became more severe. Indeed, in the past, LNG ships were allowed to operate either in full or empty tank conditions, while today there is sometimes necessity to allow operating at any filling level (see Annex 1, H “Zalar”). This requirement introduces serious difficulties in the design of both the CCS and the associated ship structure. Violent sloshing motions may occur (Fig 2) and the direct consequence is the occurrence of different impact conditions, which can induce large structural loadings possibly damaging both CCS and the associated inner-hull structure.

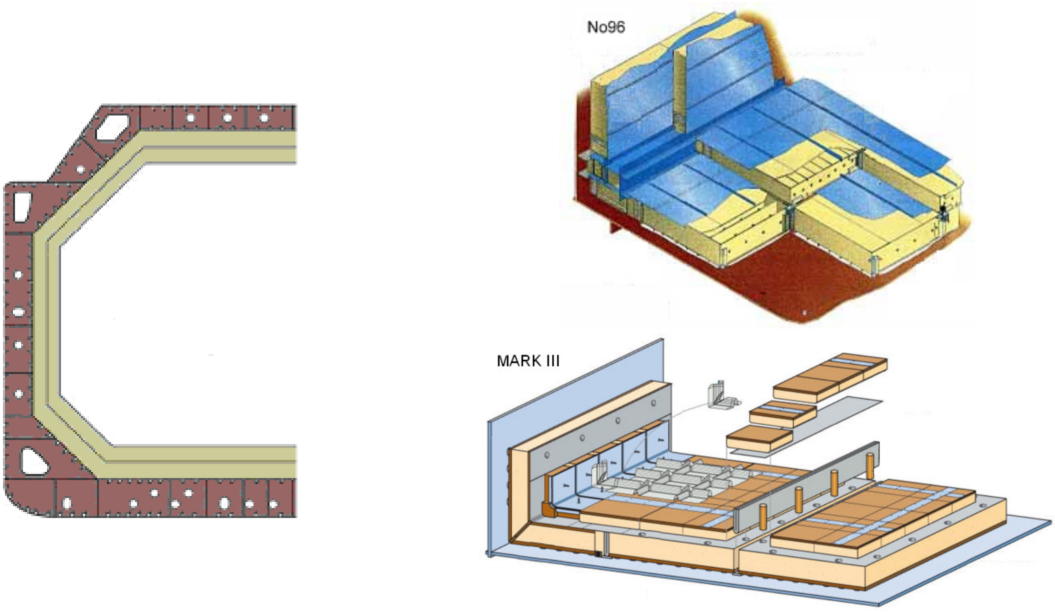

Figure 1: Membrane type LNG tank and different containment systems (courtesy of GTT)

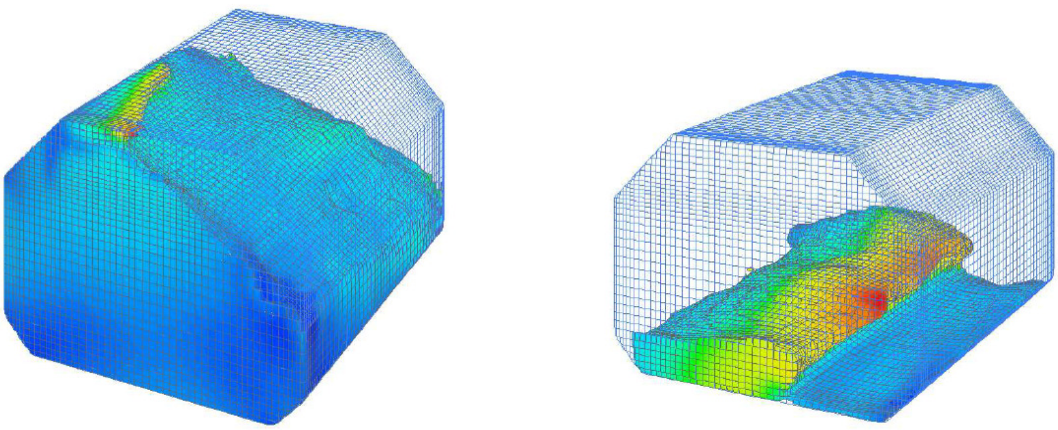

Figure 2: Typical sloshing motions

2.2 Sloshing phenomenon

Sloshing may be defined as a violent behavior of the liquid contents in tanks that are subjected to the external forced ship motions on the sea. Sloshing is a highly non-linear phenomena affected by many parameters.

First, sloshing is a large scale phenomenon. Indeed, the global flow inside the tank is governed by the ship motions, tanks' geometry, filling levels inside the tanks and LNG density. So accurate ship motions prediction is of fundamental importance in order to study sloshing.

Second, sloshing is also a small scale phenomenon. Indeed, impact pressures are strongly influenced by local phenomena such as local geometry (raised edges of the CCS), gas/liquid mixture (density ratio between the gas and the liquid, gas and liquid compressibility) or surface tension.

These local effects have a large influence on the local peak pressures which explains their high variability and non uniformity over the tanks' boundaries. Thus, sloshing is a highly stochastic phenomenon. This highly stochastic behavior is clearly observed in the few sloshing events which occurred at sea (see Annex 1, B "Gervaise") and during the sloshing model tests (pressures do not repeat themselves even under same drive motions).

Moreover, sloshing phenomenon is also complex from a thermodynamic point of view. Indeed, partial condensation of the LNG vapor (depending on the speed of condensation and impact duration) may happen during the impacts.

In addition to these pure fluid mechanics problems, another important issue due to the flexibility of the CCS is the effect of hydroelasticity (see Annex 1, I "Malenica"). Indeed, due to the violence of the impacts, the hydrodynamic pressure will often depend on the structural response so that fully coupled hydro-structure modeling is necessary. In Fig 1, two typical containment systems which are in use today are shown. The first one is the so called NO96 system, which is composed of plywood boxes filled with perlite, while the second system, called MARK III, is composed of different levels of foam combined with a plywood structure. On the side in contact with LNG, NO96 has its membrane made of special metal alloy called invar whereas membrane of MarkIII system is made of stainless steel. In the case of NO96 CCS, this membrane is flat, while it is corrugated for MARK III CCS. Correct structural modeling of such a complex structure is still challenging even for most sophisticated numerical tools based on the well mastered finite element method.

Impacts on a ship tank are associated with violent liquid motion and many possible impact scenarios are to be considered. A summary flow chart is presented in Fig 3.

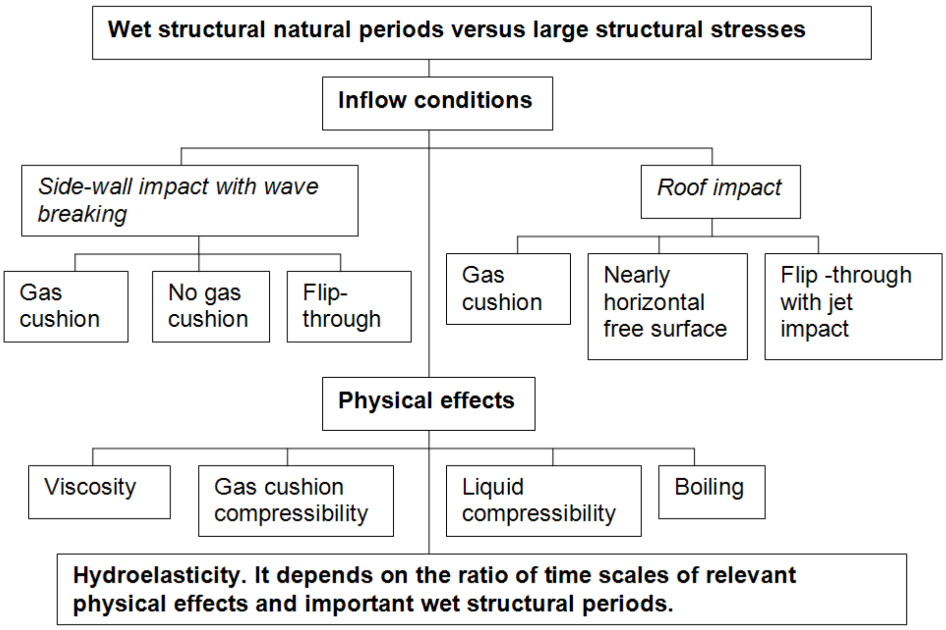

Figure 3: Summary flow chart of different impact scenarios (see Annex 1, G "Faltinsen, 2009")

Due to all the difficulties related to the correct evaluation of the hydro-structure interactions during the sloshing impacts in the tanks of LNGC or offshore LNG floating units the direct (absolute) approach seems still not to be feasible and the so called comparative approach is usually employed. The main idea of the comparative approach is to compare loading and/or structural responses of the new design with the reference case (see [2.5]).

2.3 Sloshing assessment procedure

When trying to reproduce the sloshing phenomenon, either experimentally or numerically, the complexity of the associated physics is emphasized:

- its both global and local behavior
- its stochastic nature
- the cryogenic environment
- the dynamics of the phenomenon
- the hydro-elastic effects occurring between the hydrodynamic loading and the structural response of the CCS
- the non-linear structural response of the CCS
- …

All these difficulties make it impossible to perform a direct evaluation of the sloshing loads and the strength of the insulation systems, at least with the current knowledge and the numerical and material resources. Therefore, this Guidance Note proposes simplified procedures that can be applied. Whenever a simplification is needed, it is clearly stated and its effects are discussed.

The global sloshing assessment procedure is summarized in Fig 4.

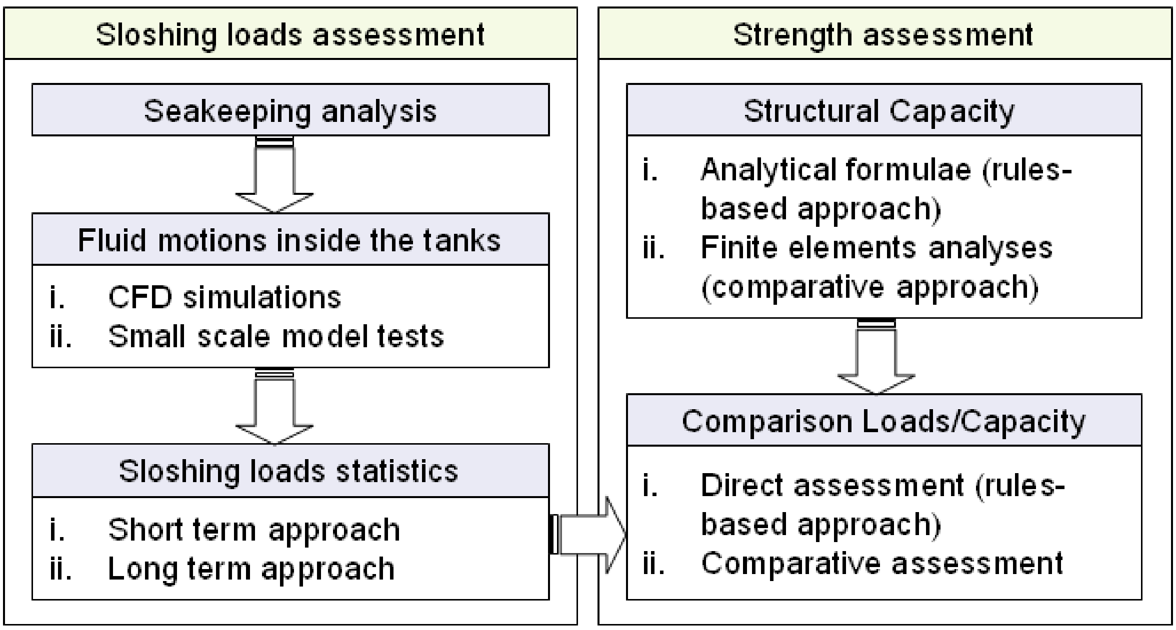

Figure 4: Sloshing assessment procedure

The sloshing loads assessment procedure corresponds to the present Guidance Note.

The strength assessment procedure is detailed in the Guidance Note NI564 "Strength Assessment of LNG Membrane Tanks under Sloshing Loads". In brief, strength assessment procedure relies on two assessment levels.

- The first level of assessment, very simplified, uses a rule-based approach to derive extreme values of allowable sloshing pressures; it is currently available for NO96 containment system only. This method relies on analytical formulae, and thus, considers many simplifying hypotheses. It should therefore only be used in a screening phase; if some areas of the LNG tank present design sloshing loads (impact pressures) larger than, or the same order of magnitude as, the allowable values analytically calculated, then a more refined analysis should be performed.
- Second, given the very large feedback available, a comparative approach may be considered. The philosophy of this approach is that, if a target ship is more resistant than a reference ship and if the latter has never sustained damages due to sloshing impact loads, then the target ship will not sustain damage either. This approach is characterized by the use of non-linear and dynamic finite element analyses, which allow us to take in consideration most of the physics involved in the structural response of CCS under sloshing loads.

As already mentioned this Guidance Note proposes only a method and gives the corresponding recommendations on the procedure to be applied. It is the designer's responsibility to opt either to use the methodology proposed in this Guidance Note, or to propose any other procedure. In any case, this choice should be discussed with the Society.

2.4 Sloshing loads assessment procedure

Methodology for sloshing loads determination (for both reference and target ships) is decomposed in the three following main steps:

- First, seakeeping analysis (see [4]) is a key point in each particular sloshing study, with an objective to determine ship motions for CFD numerical simulations and sloshing small-scale model tests.
- Second, CFD numerical simulations (see [5]) are required for an independent review of the model tests (submitted by the designer), for the quasi-static pressure calculations to be applied on IHS (behind the CCS) for its structural assessment and for the pump mast strength assessment.
- Third, sloshing model tests (see [6]) and their statistical post-processing (see [7]) aim to determine the design sloshing loads (as a function of the loaded area) at model scale using a probability-based framework relying on the long term approach:
  - Design sloshing loads are to be determined as a function of loaded area since each structural capacity is a function of the loaded area
  - The long term approach used under the probability-based framework is justified as follows. Both observations of the few sloshing events which occurred at sea and sloshing model tests clearly indicate variability of sloshing pressures (see Annex 1, B "Gervaise"). This high variability of sloshing pressures result in a flat tail exceeding probability curve. As a consequence, a small change in the probability level (which means return period) can have strong influence on the statistical pressure. This is the reason why all navigation conditions associated with their expected return period (long term approach) are to be taken into account.
  - The long term approach associates to each one of the sailing condition the ship will face during its lifetime the two following characteristics. First, a short term exceeding probability function of sloshing impact pressure is associated to each sailing condition. Second, a probability of occurrence is associated to each sailing condition. Then the contribution of all the sailing conditions can be cumulated together which results in a long term exceeding probability function (see Annex 1, A "Diebold") at model scale (see 7.3]).
  - Due to the size limit of the sample, parameters estimation is not exact, but remains random. From designer point of view, punctual estimation is meaningless. A safety margin corresponding to the risk acceptance of the underestimating load pressure is to be provided by the confidence intervals.

The sloshing loads assessment procedure is summarized in Fig 5.

Finally, the reference vessel is used to determine the scaling factor λ from model scale to full scale (see [7.5] and NI564, Sec 3, [5]). To assess the target vessel, the small scale design loads of the target ship at the desired return period are scaled by this factor λ and by a safety factor (SF) taking into account the long term confidence intervals, and compared to the capacity of the target vessel (see [7.5] and NI564, Sec 3, [5]).

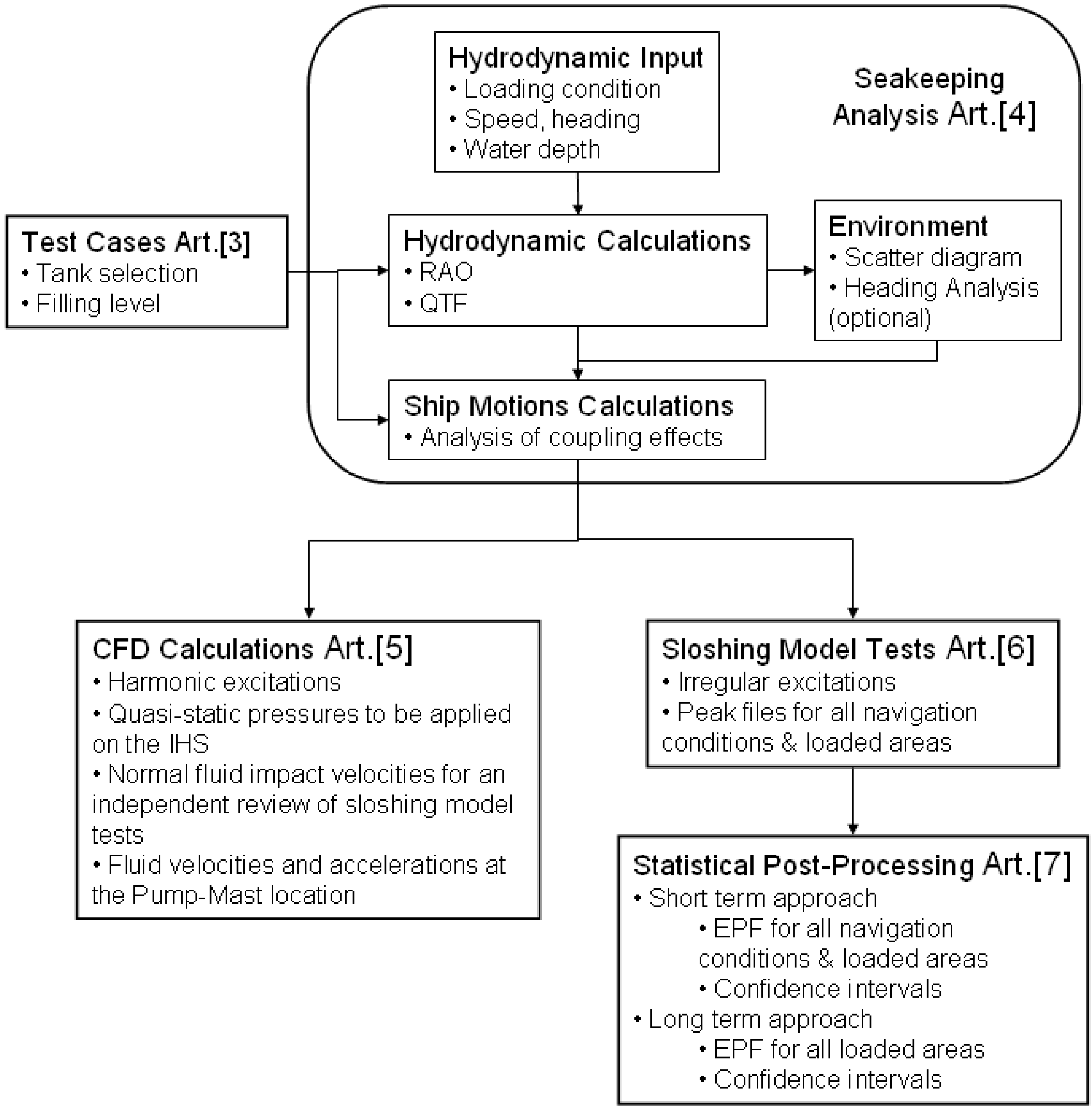

Figure 5: Sloshing loads assessment procedure

2.5 Design reference sloshing loads

The reference case is a 4-tank LNGC with a capacity of 130,000 to 155,000 m^3 with world wide service conditions. As a rule and at the beginning of 2011, the allowable filling levels for this reference case (ships with a capacity from 130,000 m^3 up to 155,000 m^3) are according to the membrane designer [0%H: 10%H] and [70%H: 98%H] for the three membrane CCS NO96, MarkIII and CS1.

The reference design sloshing loads associated with these allowable filling levels are calculated using the long term approach (see [7.3]).

3. Basic considerations and test cases

3.1 Basic considerations

Basic considerations in general sloshing analysis are given to a selection of configurations to be studied, with respect to the following parameters:

- type, size and capacity of the vessel
- service speed
- mooring type in the terminal operation
- vessel loading plan and service definition
- general tank arrangement
- tank geometry and proportions
- tank filling levels with reference to loading plan
- environmental conditions with reference to service definition.

3.2 Test cases

The first stage of liquid motion analysis is the selection of an initial test cases list, aimed to benchmark the amount and type of studies to be performed. Initial selection is based on the first review of the design concept with respect to ship general arrangement, service specification and loading plan.

Aimed to define governing cases, basic considerations are given to determine the following parameters:

- number and location of representative tanks
- relevant filling levels
- type and nature of the fluid flow inside tanks.

Initial test cases list is further developed into the test specification with respect to the subsequent analysis of ship and tank motion interaction.

3.3 Selection of studied tank

All the tanks which may experience sloshing are to be considered. The parameters to take into account for the studied tank are the following:

- Shape of the tank: this parameter may be important since a smaller tank may give higher sloshing loads than a bigger tank even for a same location.
- Position of the Tank. Longitudinal and transverse distances from the centre of gravity to the centre of the tanks are to be considered:
    - Hence for the tanks having the same dimensions, the sloshing study is governed by the criteria of the most solicited on-board the vessel ie located at the furthest distance from the vessel centre of gravity.
    - For a two-row tank arrangement, a dedicated hydrodynamic analysis is to be performed in order to select the portside or starboard tank by considering longitudinal and transverse motions and accelerations.

The selection of the studied tank should be discussed and agreed with the Society.

3.4 Liquid flow types

Fluid flows generated in membrane tank of LNGC or offshore LNG floating units may have different shapes and sloshing impacts may occur at different locations, depending on tank filling height, magnitude of ship motion and range of dominant motion periods. Based on numerous model tests and numerical computation, sloshing impacts can be classified in two basic groups (Fig.6 & Fig.7):

- Low fillings:

  Hydraulic bores and progressive waves appear moving back and forth between tank walls. Generally, wave front may be inclined or with the entrapped gas pocket and impacted surface is very large.

- High fillings:

  Standing wave appears moving upwards and downwards with one or two nodes depending on excitation period. Generally, waves are breaking in the tank corners and impacted surface is rather local.

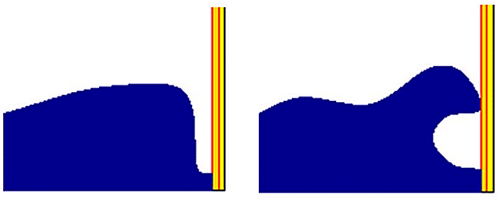

Figure 6: Progressive wave and gas pocket at low fillings

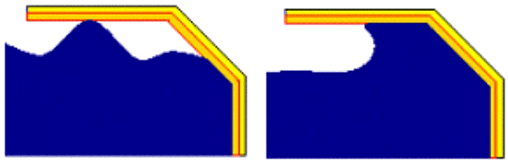

Figure 7: Standing and braking wave at high fillings

3.5 Tank fillings

Generally, selection of filling levels to be studied is based on the return experience from the sloshing studies and LNG vessels in operation. The filling levels selection is to be discussed and agreed with the Society.

3.5.1 Standard filling levels

Standard filling levels are considered within conventional intervals:

- from 70% of tank height to 98% of tank height
- from 0% to 10% of tank height.

This status is under continuous review, so consult the Society for the current situation.

3.5.2 Partial filling levels

Selection of relevant partial filling levels is particular for each project, related to the service specification, tank geometry, size and proportion of main tank dimensions. Specification of partial filling levels results from the investigation of liquid flow types that are likely to be induced during the vessel's operation.

However because higher sloshing loads are likely to occur at low partial fillings, these low partial fillings need to be studied in details. Thus, here is an example of the fillings to be studied (15%H, 20%H, 25%H, 30%H, 40%H, 50%H, 60%H).

The fillings' selection should be discussed and agreed with the Society.

4. Seakeeping analysis

4.1 Objective

Seakeeping analysis is a key point in each particular sloshing study, with an objective to determine ship motions. Directly calculated ship motions determined by such analysis are used as sloshing excitation for CFD calculations and sloshing model tests.

Requirements of the present Article are complementary to the Guidance Note for the Classification of Offshore Floating Gas Terminals (NI542) which remains applicable, except where otherwise specifies.

4.2 Hydrodynamic calculations

The purpose of the hydrodynamic calculations is mainly aimed to determine Response Amplitude Operators (RAO) of the six degrees of freedom motion, presenting the ship response on the wave of unit amplitude as a function of wave frequency.

4.2.1 Introduction

Hydrodynamic computations are generally performed by means of 3D-panel diffraction/radiation potential theory within the frequency domain software. This software has to be fully validated through the comparisons with semi-analytical studies, numerical results from recognized numerical tools and experimental results. The objective of sea keeping calculations is aimed at determining wave induced loads and ships responses under a prescribed sea state. General procedure of 3D sea keeping analysis includes following main steps detailed in [4.2.2] to [4.2.4]:

- preparation of input data
- hydrodynamic computation.

4.2.2 Preparation of input data

- Hydrodynamic panel model:
  The ship's hull is represented by flat panels (quadrilateral or triangular). To prepare the input data, following information must be provided:
  - body plan and offsets including length between aft and forward perpendiculars, width and drafts at given loading conditions, displacement and block coefficient
  - ship's inertia described by the coordinates of the center of gravity and gyration radii at given loading conditions. Particular attention shall be paid on the calculation of the roll radius of gyration. Indeed, this roll radius of gyration will directly impact roll natural period of the ship which is an important parameter of the sloshing flow.
  - hydrodynamic input including water depth, ship's hull speed
  - mooring stiffness, presence of quay and/or other nearby floating bodies.

  A pre-processor is generally used to generate hull mesh (of usually about 2000 flat panels) for a given set of offset lines and inertia matrix for a given mass distribution.

  One example of hydrodynamic model accounting for coupling effects due to the interaction of vessel motion and tank liquid motion is presented hereafter (see [4.2.4]). Such model is composed of ship hull and tank 3D-panel meshes (Fig 8).

- Loading conditions for sloshing study with conventional fillings:

  Loading conditions selected for sloshing study with conventional fillings are distributed with reference to high and low fillings range.

  For low fillings, covering range from 0% - 10%H, considered loading cases are:
  - ballast condition
  - condition(s) where tanks can be filled up to 10%H. Indeed for some return voyages where tanks can be filled up to 10%H, taking into account sloshing effects in the ship motions calculations may increase the design sloshing loads in comparison with the classical ballast condition [4.2.4].

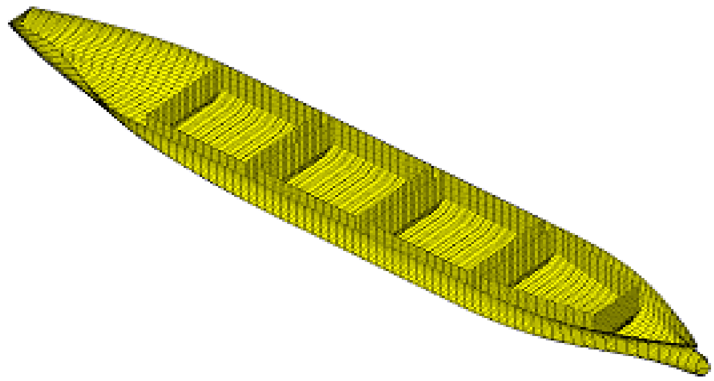

Figure 8: 3D-panel coupled model

For high fillings, covering range from 70%H - 98%H, considered loading cases are:

- filling 70%H in all cargo tanks
- filling 80%H in all cargo tanks
- full load condition, representing the case with the worst hydrostatic properties from Loading Manual.

- Loading conditions for sloshing study with partial fillings:
  Loading conditions selection for sloshing study with partial fillings is to be discussed and agreed with the society. In particular, coupling between ship motions and liquid motions inside the tanks is to be analyzed (see [4.2.4]).

4.2.3 Hydrodynamic calculations

The analysis of hydrodynamic loads and vessel motions is usually performed in the frequency domain, using 3D hydrodynamic model of the vessel (see [4.2.2]). For each loading case, hydrodynamic model is composed of the geometry of submerged part of the hull and of the corresponding weight distribution. For a set of wave frequencies (generally 50 to 70) and headings (a minimum step of 15° is required), transfer functions i.e. Response Amplitude Operators (RAO) are obtained by running the hydrodynamic software for a regular wave of unit amplitude. They include:

- wave induced global loads
- motions, velocities and accelerations RAO at any point of the ship
- water added mass and damping matrices
- dynamic pressures on the ship hull
- wave induced loads at different ship sections
- wave kinematics to estimate relative motions, air-gaps, slamming occurrences, etc
- Quadratic Transfer Functions (QTF) which are required in order to perform the wave heading analysis and mooring system simulations.

In case of spreading, a minimum step of 5° is required for the headings.
For the ship's speed and wave headings to be computed, see [4.3].
One has to notice that real ship motions can not be calculated at this stage since environmental data have not been considered.

4.2.4 Seakeeping/sloshing coupling

Usually, state of the art of sloshing analysis relies on small-scale sloshing model tests supported by extensive developments of CFD computation techniques, commonly studying one isolated tank submitted to the forced motion without their mutual interaction. In reality, wave-induced response of the vessel carrying liquid cargo is affected by internal liquid motion, and consequently, tank liquid flow is altered by the vessel motion in return as figured in Fig 9.

The roll (the most affected degree of freedom due to coupling) RAO comparison between non coupled and coupled motions is figured in Fig 10. The motions affected by the coupling are the surge, sway, roll and yaw motions. More particularly for roll motion, we can observe the two characteristic peaks of a coupled system (ship + tanks). The first peak is associated with the motions of the ship and the second one with the internal liquid motions in the tanks.

This seakeeping/sloshing coupling which modifies the ship motions may have consequently some influence on induced sloshing design loads.

The hydrodynamic software has to take this seakeeping/sloshing coupling into account and should be validated through comparison with experimental results.

For the particular case of double-row tank arrangement, the partial filling effect is believed to be adequately treated by correcting the hydrostatics stiffness.

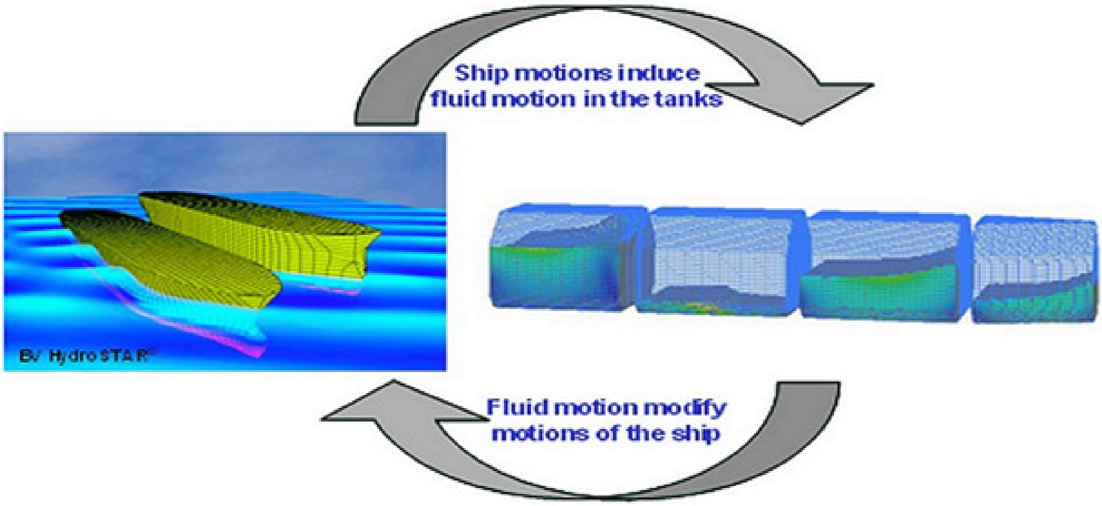

Figure 9: Direct non-linear coupling - HydroSTAR® & CFD calculations

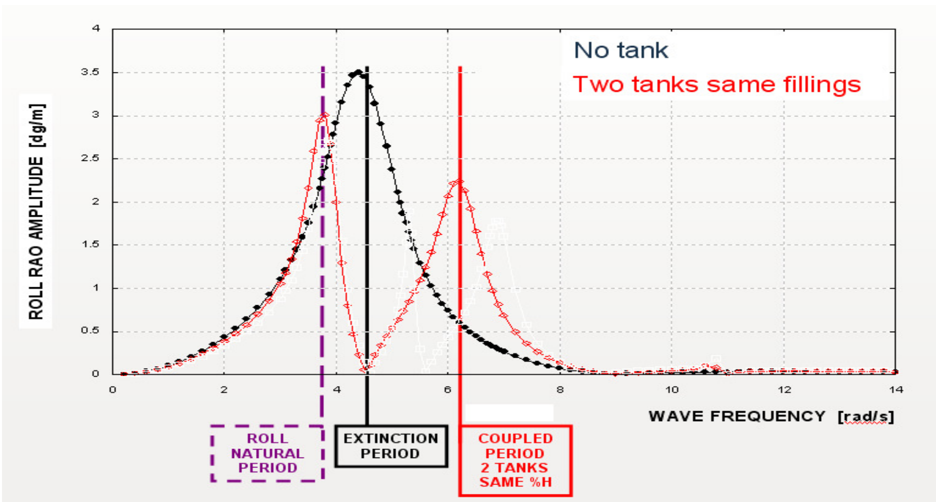

Figure 10: Roll RAO comparison for non coupled (black line) and coupled motions (red line)

4.3 Environmental conditions

Environmental conditions to be provided for sloshing analysis of LNGC or offshore LNG floating units are the description of wave data corresponding to the service specification. Moreover for offshore LNG floating units, site specific wind and current contributions are required in order to perform a wave heading analysis (see [4.3.2.1]).

4.3.1 LNGC with world wide service conditions

4.3.1.1 IACS scatter diagram

For LNGC with world wide service conditions, environmental data for sloshing analysis refer to North Atlantic trade route with significant wave height envelope fitted to 40-years return period.

North Atlantic trade route conditions are defined by Standard Wave Data (IACS Rec. 34, Rev. 1 June 2000). The North Atlantic wave scatter diagram is presented on Fig 11.

Sea-states from scatter diagram are modeled by spectral density function i.e. wave spectrum, presenting a distribution of wave energy per wave frequency. Pierson-Moskowitz spectrum formulation (derived from the North Atlantic observations) is applied for fully developed seas, described as following:

$$S(w) = \frac{1}{4\pi} H_s^2 \left(\frac{2\pi}{Tz}\right)^4 w^{-5} e^{-\frac{1}{\pi}\left(\frac{2\pi}{T_z}\right)^4 w^{-4}}$$

where ω denotes the wave circular frequency (rad/s). The assumption of short crested seas with a spreading function may be applied. The value of the cosine spreading function should be discussed and agreed with the Society.

Hs/Tz	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	SUM
0.5	0.0	0.0	1.3	133.7	865.6	1186.0	634.2	186.3	36.9	5.6	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	3050
1.5	0.0	0.0	0.0	29.3	986.0	4976.0	7738.0	5569.7	2375.7	703.5	160.7	30.5	5.1	0.8	0.1	0.0	0.0	0.0	22575
2.5	0.0	0.0	0.0	2.2	197.5	2158.8	6230.0	7449.5	4860.4	2066.0	644.5	160.2	33.7	6.3	1.1	0.2	0.0	0.0	23810
3.5	0.0	0.0	0.0	0.2	34.9	695.5	3226.5	5675.0	5099.1	2838.0	1114.1	337.7	84.3	18.2	3.5	0.6	0.1	0.0	19128
4.5	0.0	0.0	0.0	0.0	6.0	196.1	1354.3	3288.5	3857.5	2685.5	1275.2	455.1	130.9	31.9	6.9	1.3	0.2	0.0	13289
5.5	0.0	0.0	0.0	0.0	1.0	51.0	498.4	1602.9	2372.7	2008.3	1126.0	463.6	150.9	41.0	9.7	2.1	0.4	0.1	8328
6.5	0.0	0.0	0.0	0.0	0.2	12.6	167.0	690.3	1257.9	1268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1	4806
7.5	0.0	0.0	0.0	0.0	0.0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1	2586
8.5	0.0	0.0	0.0	0.0	0.0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1	1309
9.5	0.0	0.0	0.0	0.0	0.0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	6.1	1.7	0.4	0.1	626
10.5	0.0	0.0	0.0	0.0	0.0	0.0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4.0	1.2	0.3	0.1	285
11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1	124
12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.0	4.4	9.9	12.8	11.0	6.8	3.3	1.3	0.4	0.1	0.0	51
13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	0.7	0.2	0.1	0.0	21
14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0.0	0.0	8
15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0.0	0.0	3
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	1
SUM:	0	0	1	165	2091	9280	19922	24879	20870	12898	6245	2479	837	247	66	16	3	1	100000

Figure 11: Probability of sea states in the North Atlantic described as occurrence per 100,000 observations (IACS Rec. 34, Rev 1 June 2000)

4.3.1.2 Ship speed assumption

The ships speeds to be considered depend on the sea state wave height and the relative wave heading between the prevailing incoming wave direction and the ship's speed (See Tab 1).

	Heading				
Wave Height, in m	Following Seas $0° < \theta < 45°$	Following Quartering Seas $45° < \theta < 60°$	Beam Seas $60° < \theta < 120°$	Following Head Seas $120° < \theta < 135°$	Head Seas $135° < \theta < 180°$
$Hs < 9$ m	V_{max}				
$Hs > 9$ m	$V_{1/2}$	Linear Interpolation	5 knots	Linear Interpolation	$V_{1/2}$

Table 1: Ship speed definition as a function of wave height and heading

4.3.1.3 Operational limits and response-based sea-states

Response-based sea-states are introduced in order to avoid ship scantling to be penalized with account for not-realistic operation conditions. Limitation of extreme motions is performed through the procedure of wave height limitation based on selected relevant operability parameters (as roll angle and vertical acceleration) according to the Society Rules recommendation (See Flow-Chart presented on Fig 12).

Wave height limitation is not neglecting occurrence of such extreme sea-states but compensating for not operable ship conditions. Other dominant parameters used in estimation of ship's operability might be verified within a list of ship's responses as lateral and longitudinal acceleration, shear force and vertical bending moment, tank reactions (forces and moments), etc… An example of wave height limitation for operability criteria is given in Fig 13.

If particularly demanded by the Client, sea-state condition will be treated without any limitation i.e. taking Scatter diagram with maximum wave-height envelope or 40 years wave height envelope.

4.3.2 Offshore LNG Floating Units

For floating systems operating within restricted water locations, following site specific environmental conditions are to be considered in the sloshing analysis:

- Site specific directional wave scatter diagram(s) corresponding to the operational location(s) of the floating system,
- Number of wave spectra composing the sea state. An arbitrary number of wave spectra can be considered. Usually, not more than 6 wave spectra can compose a sea state.
- For each wave spectrum, the following data are to be provided:
  - wave spectrum properties:
    - Pierson-Moskowitz with associated (*Hs, Tp*)
    - Jonswap with associated (*Hs, Tp, γ*)
    - Gauss with associated standard deviation (*Hs, Tp, σ*)
  - Spreading (if any) and the value of its cosine spreading function
- Water depth at the operational location(s)
- Wind direction and magnitude
- Current direction and magnitude.

Wind, current and prevailing wave spectra directions (= incidences) are the angles from which each of the components arrive to the floating system. They are defined in the global reference system with respect to North.
All these data provided by hindcast data for instance are to be reviewed and agreed by the Society.

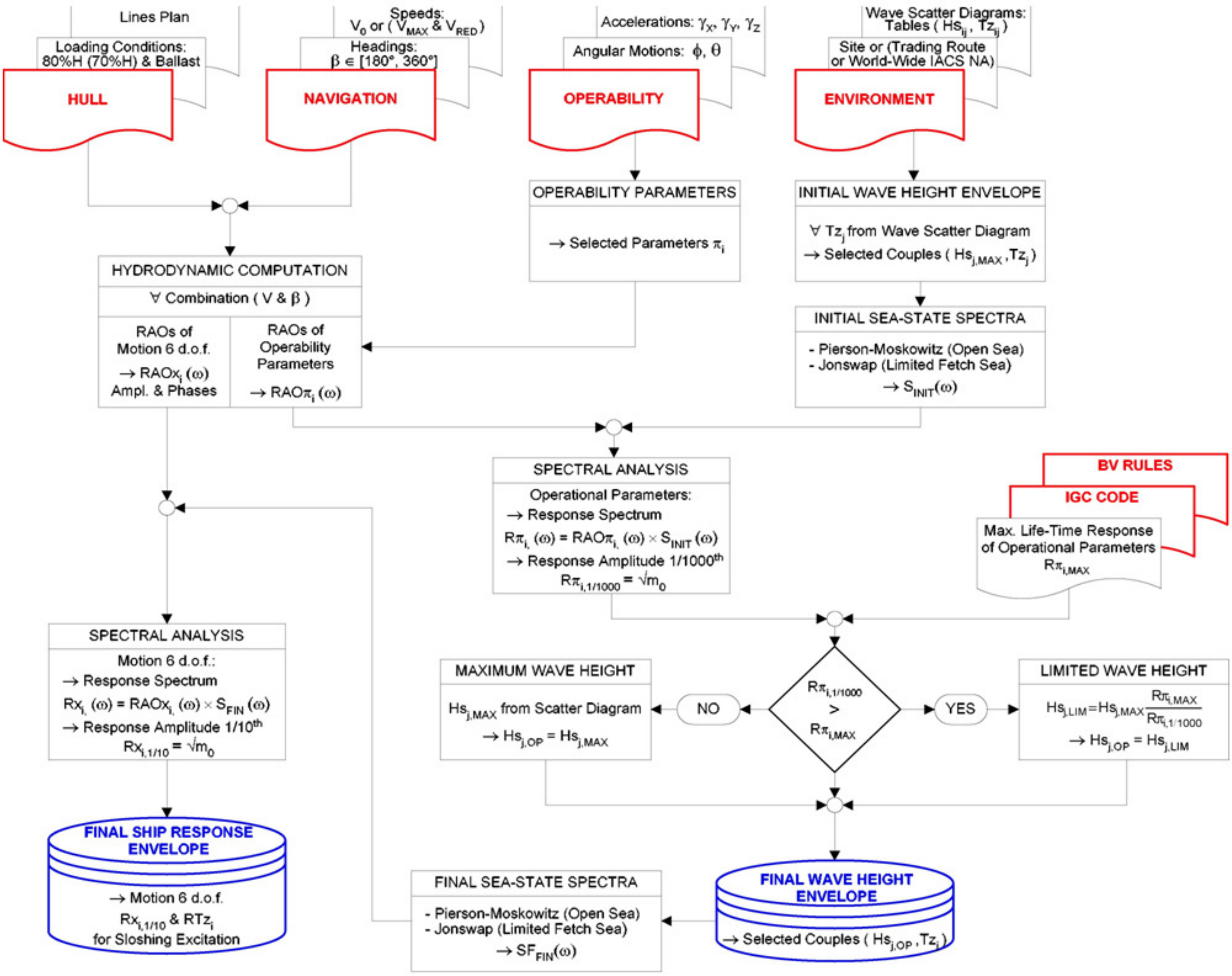

Figure 12: Sea-state selection procedure for response-based sea-spectra

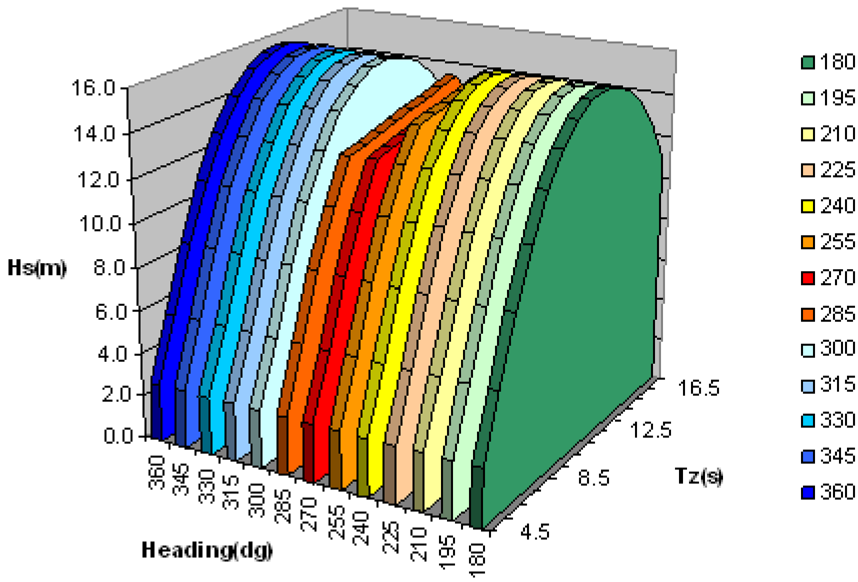

Figure 13: Example of IACS Res. 34 Wave-height limitation for operability criteria

4.3.2.1 Wave heading analysis for LNG Terminals

For offshore LNG floating units operating within restricted water locations, the unit is usually moored. Depending on the mooring (spread or turret moored) used for these units, the unit will not face the waves similarly. Indeed, in case of spread mooring the vessel will be always aligned in the same direction. The wave heading calculations are thus straightforward.

For turret-moored offshore LNG floating units, a wave heading analysis is to be provided. The objective of this heading analysis is to calculate the heading of the vessel submitted to an arbitrary number of wave spectrum composing a sea state (usually wind sea and swell), wind and current provided through a met-ocean database. Computations are performed using a mooring software.

Hydrodynamic properties of the unit, required by the mooring software and computed by the hydrodynamic software, refer to the added mass coefficients, 1st order motions (RAO) and 2nd order motions (QTF). Additional linear damping due to the mooring system is to be evaluated in agreement with the Society.

Environmental conditions to be provided are listed in [4.3.2].

Aerodynamic properties of the vessel are to be provided. These aerodynamic properties, required for the mooring analysis model, refer to vessels' areas exposed to the wind and wind force coefficients.

Finally, the heading of the vessel is calculated for all the sea-states and its dependence on met-ocean data (wind sea, swell, current or wind) analyzed.

A result example of such wave heading analysis for a 10 year hindcast database is figured out in Fig 14.

The headings 0°, 180° correspond respectively to the head and following seas. On Fig. 14, one can notice that from one hand the vessel is aligned with the highest waves (relative heading close to 0° for highest Hs) and on the other hand that only small Hs occur for beam seas.

This behavior is very important since the most critical cases in terms of sloshing loads occur for beam seas at low partial fillings (LNG height between 10%H and 40%H where H denotes the tank height). Thus neglecting the results of the wave heading analysis may lead to over predict the sloshing loads by considering too high (unrealistic) beam seas conditions. This is the reason wave heading analysis for turret moored offshore LNG floating units is recommended.

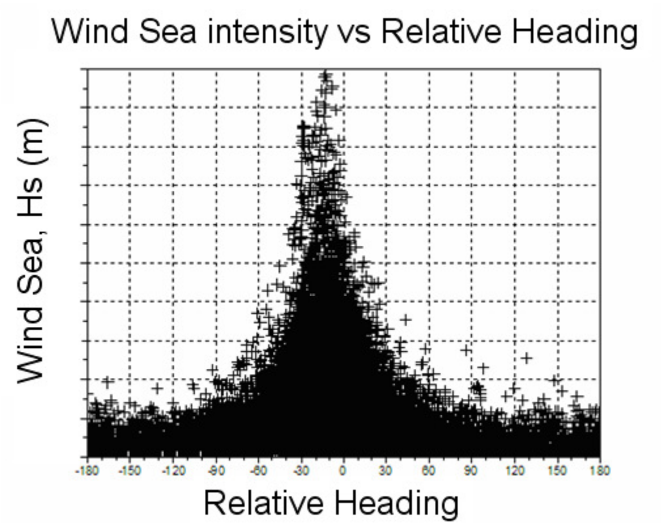

Figure 14: Wind sea intensity versus relative heading between the wind sea and the vessel

4.4 Short-term spectral analysis

The objectives of the spectral analysis are to determine:

- the spectral moments for the 6 degrees of freedom motion
- the parameters of short term response used as sloshing excitations for the CFD calculations.

After having obtained the transfer functions, the responses (loads, motions, pressures, etc) in irregular waves of a given wave energy spectrum can be obtained by performing spectral calculations. Analysis can be performed using a unique or multidirectional wave spectrum with or without spreading. The results include significant magnitude and average period of the response.

Once, when Response Amplitude Operators (RAO) i.e. Transfer Functions $TF(\omega,\theta)$ are calculated and energy sea-spectrum $S_{\xi}(\omega)$ defined, short term responses are calculated through the spectral moments. Spectral moment of nth order is:

$$m_n = \sum_{i=1}^{Ns} \int_0^{\infty} \int_0^{2\pi} D_i(\theta) \cdot S_i(\omega) \cdot |TF(\omega)|^2 \, \omega^n \, d\theta d\omega$$

where:

N_s Number of wave spectra describing the sea state

$S_i(\omega)$ ith wave spectra (Pierson-Moskowitz, JONSWAP, Gauss or whatever function of ω)

$D_i(\theta)$ ith spreading function associated with the ith wave spectra

ω Pulsation or circular wave frequency (rad/s)

θ Relative wave heading between the wave and the vessel. In some cases, the motion can be out of the axis of the vessel. The hydrodynamic software is to be verified for such kind of calculations.

The spreading function $D_i(\theta)$ equals to the Dirac function in case of unidirectional waves or $\cos^n(\theta)$ in case of spreading with n to be agreed with the Society. Response amplitude is proportional to the square root of the spectral moment of 0th order, i.e. proportional to the surface under the response energy spectrum. In case of response amplitude on 1/10th level, we use the following proportions with spectral moment of 0th order:

$$R_{1/10} = 2{,}54\sqrt{m_0}$$

and

$$R_{1/1000} = 3{,}72\sqrt{m_0}$$

By assuming a Gaussian process, the Rice formula induce that the mean zero-crossing period is:

$$RT_Z = 2\pi\sqrt{m_0/m_2}$$

The response amplitude on the 1/10th level and the mean zero-crossing period are to be used as sloshing excitations for the sloshing numerical calculations.

4.5 Sloshing excitation

Sloshing excitation presents ship response on selected sea-states that is to be imposed to either small-scale model test or numerical tank.

Sloshing excitation includes all 6 degrees of freedom motion and can be given in following forms:

- Harmonic excitation for CFD calculations:

  Each of 6 degree of freedom motion is described by its amplitude on 1/10th level, zero-crossing period and phase. Motion amplitude and period are short-term values resulting from spectral analysis [4.4], whilst phase origins from Response Amplitude Operators.

- Irregular excitation for sloshing model tests:

  Irregular input motions are specified for the same sea-state as selected for harmonic excitation, given as tabular data for the 6 degrees of freedom.

  These irregular excitations are derived from seakeeping calculations. The ship motions RAO are combined with a minimum of 200 elementary components of the wave spectrum for which the phase is defined with a random number. The obtained harmonic motions are then recombined in order to get irregular time history of the ship's motion for each degree of freedom. For longer tests duration required for statistical convergence (10 hours full scale and more), different random numbers are generated in order to create different time histories from the same spectrum.

Once obtained the 6 degrees of freedom time motion histories, a spectral analysis is to be performed in order to compare the obtained (m_0, m_2) moments values with the theoretical ones. The obtained differences are to be documented.

5. CFD calculations

5.1 Objective

The objective of the CFD numerical sloshing simulations is to evaluate the overall fluid kinematics, to provide independent verification of sloshing effects on cargo tank walls, to evaluate the representative design loads on ship inner-hull structure and to provide fluid velocities and accelerations at the pump mast location for its strength assessment.

5.2 Introduction

First of all, it should be recognized that the evaluation of LNG impact pressures by numerical CFD analysis is not reliable. High impact pressure is strictly localized in the space and the time, being very sensitive to the local effects. Thus, it depends on many physical parameters of liquid, gas and structure involved in the impact (such as density, viscosity, ullage pressure, surface tension, compressibility, hydro-elasticity, visco-elasticity, cryogenic environment with free surface condition at boiling point of gas etc...).

For all these reasons, the present Guidance Note suggests using sloshing CFD analysis to identify type and nature of the impact, to accurately evaluate kinetic energy of the liquid and "quantify" impact by the impact normal velocity with respect to the wall at distinct locations (predefined hot-spots).

This information is of fundamental importance for the independent review of the sloshing model tests and for the comparative analysis with reference vessels.

Second, structural impact tests and dynamic finite element analyses show that impact peak pressure is filtered and averaged by containment system when the impulse arrives to steel back-up structure. Thus, the quasi-static pressure directly calculated by CFD is provided for the structural assessment of the inner-hull structure as described in NI564, Sec 2, [2]. Nevertheless, peak pressure is taken into account by amplification of quasi-static pressure by partial safety factor.

At last, fluid velocities and accelerations at the pump mast location are processed using the Morison equation in order to evaluate hydrodynamic loads acting on this pump mast. These hydrodynamic loads acting on the pump mast are used for its strength assessment (NI564, Appendix 1).

5.3 Numerical model

5.3.1 Generalities & requirements

Numerical sloshing analyses are to be carried out using recognized and validated numerical CFD software. Mathematical formulation of such CFD software is to be based on Navier-Stokes equations (mass and momentum conservation). Such CFD tool is to be capable from one hand to track accurately the free surface by solving a free surface equation and on the other hand to reproduce an arbitrary prescribed 6 degrees of freedom motions.

Mainly, such CFD software use from one hand Finite Volume Method (FVM) as discretization method and on the other a Volume Of Fluid (VOF) method modeling technique in order to track and locate accurately the free surface. Each cell of VOF mesh is filled with either liquid or gas/void and a free surface presence is defined by the corresponding fraction of fluid as the filling rate of the cell by the liquid phase.

Other computational methods such as Smooth Particle Hydrodynamics (SPH) (mesh free Lagrangian method) can be used if validated.

The choice of CFD software for the sloshing numerical calculations is to be agreed with the Society.

5.3.2 Validation of CFD tools

Beside classical validation cases that each CFD tool is to address, present Guidance Note requires additional validation specific to sloshing physics.

5.3.2.1 Drop tests

CFD tool is to be validated against drop tests. This experiment consists in dropping one wedge equipped with pressure sensors on a liquid surface at rest. For wedges with dead-rise angles greater than 5°, Wagner's solution for pressure is proved to be satisfactory (see Annex 1, F: "Wagner"). Thus, several simulations at different heights are to be carried out and the measured time pressure histories are to be compared to the Wagner's reference solution. If the difference is too high, the CFD tool should be rejected.

Such comparison is depicted on the Fig 15. One can notice the excellent agreement between the CFD & the Wagner's reference solution.

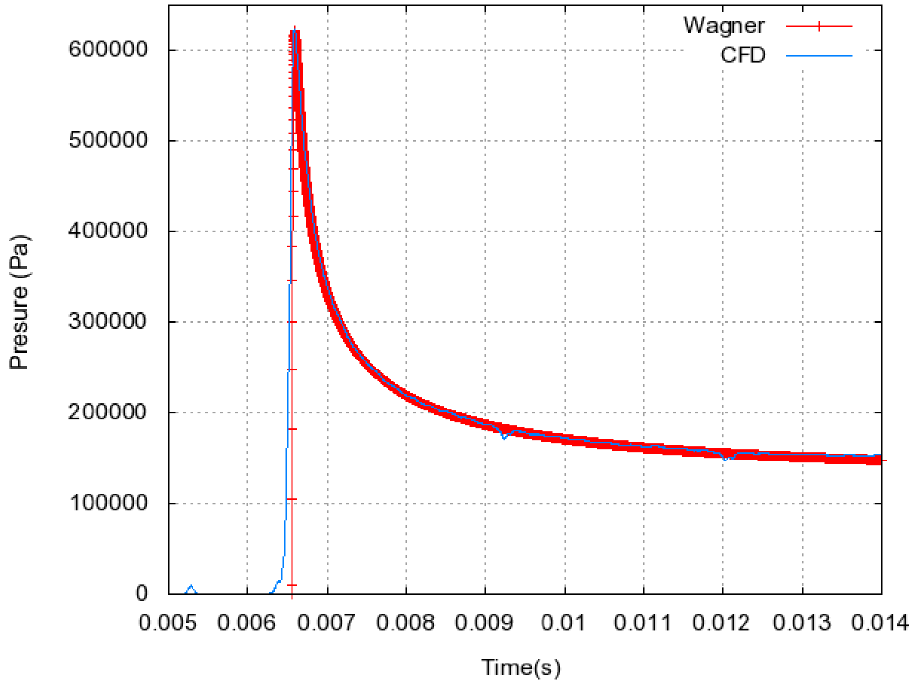

Figure 15: Comparison OpenFOAM (CFD raw data ie no filtering ⇨ green curve)/Wagner (analytical solution ⇨ red curve) for two pressure sensors along the wedge.

5.3.2.2 Free Surface and Global Forces

Second, such CFD tool is to be validated for the free surface elevation, kinematics inside the tank and global forces calculations. This validation consists in comparing the free surface elevation and the global forces time histories calculations to these ones observed and measured during experiments (see Annex 1, E: "Moirod") for different filling ratios.

Such validation is given in (see Annex 1, E) where a pure harmonic sway motion was imposed to the tank for different filling ratios and for different frequencies refined around the theoretical resonant frequency at the studied filling height.

First, one can notice the excellent agreement between the calculated free surface elevation and the observed one during experiments (at the same instant) as depicted on the Fig 16 and Fig 17.

Second, one can notice the excellent agreement regarding global forces time histories between the CFD calculations (OpenFOAM & Flow3d) and the experiment as depicted on Fig 18.

Finally, more sophisticated Particle Image Velocity measurements by application of a laser technique can be envisaged for a verification method. Such kind of CFD validation can be requested, accompanied with justification of the measurement accuracy.

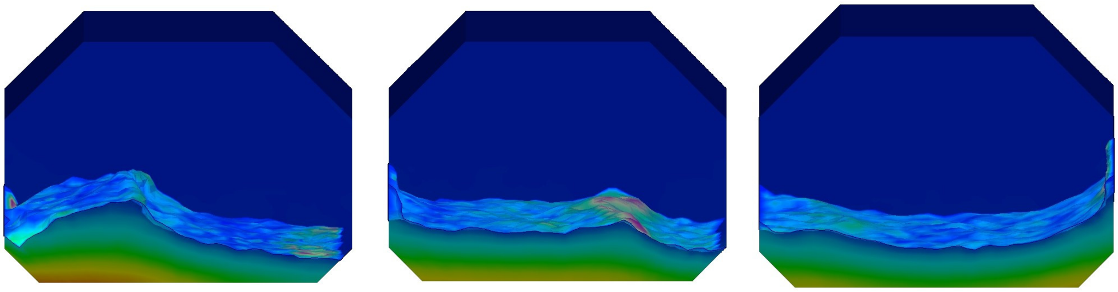

Figure 16: Instant captures from OpenFOAM-20%H - 1m(FS)- T=1.41s

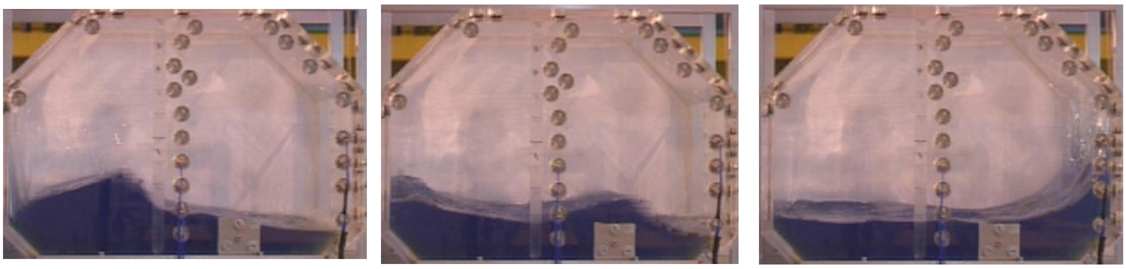

Figure 17: Instant captures from EXP. - 20%H - 1m(FS) - T=1.41s

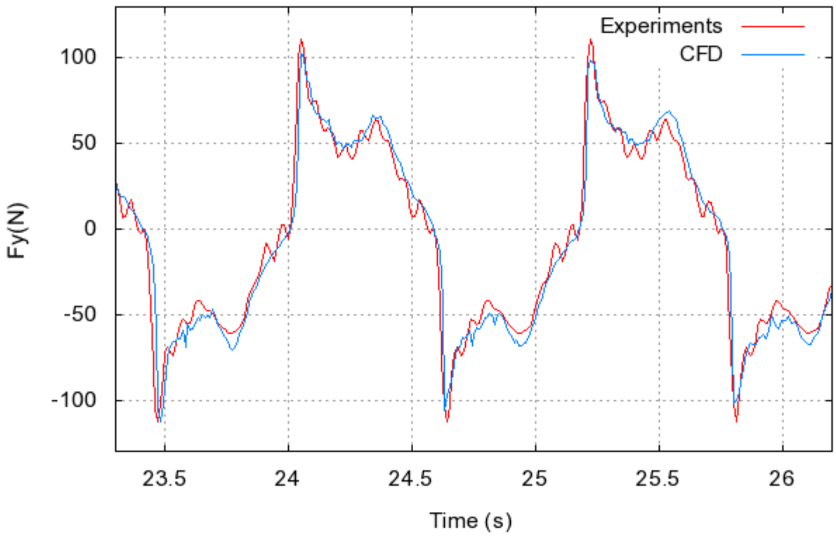

Figure 18: Fy time series comparison-20%H

5.4 Problem modelization

5.4.1 Mesh

There is an amount of different parameters to be set-up in CFD input to achieve realistic fluid flow conditions. Notably, there is grid dependence and sensitivity to parameters used in numerical differentiation and iteration procedures, as automatic adjustment of the convergence criterion in the pressure iteration algorithm in order to fulfill continuity equation.

Tuning of CFD tools parameters resulted from variation study of the mesh size and convergence criterion adjustment, until mass conservation being satisfied with reasonable demand on computer resources as a storage and CPU time.

Example of typical VOF mesh for a membrane tank of LNG Carrier is given on Fig 19 to Fig 21.

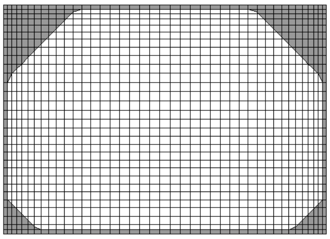

Figure 19: Mesh configuration Transverse section (yz view)

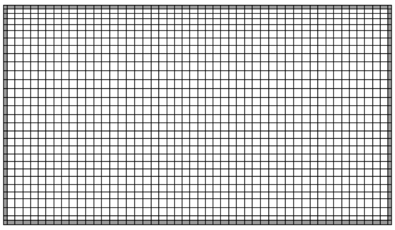

Figure 20: Mesh configuration Longitudinal section (xz view)

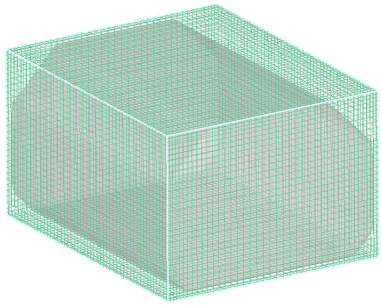

Figure 21: Mesh configuration 3D view

5.4.2 Predefined hot spot zones

Impact velocities and quasi-static forces (per square meter, i.e. quasi-static pressures) are examined in predefined zones located at different hot-spots inside the tank (similar to the definition of pressure sensor location inside the physical small-scale model tank). Each hot spot is defined by a zone composed of several cells, usually nine of the same size. Location of these hot spots depends on filling height and sloshing excitation imposed to the tank.

The default hot spot zones are located on:

- transverse bulkheads above the lower chamfers height, to investigate the consequence of longitudinal sloshing flows, including the phenomena of longitudinal progressive wave
- side-walls above the lower chamfers height, to investigate the consequence of transverse sloshing flows, including the phenomena of transverse progressive wave
- each corner between the upper chamfer and the ceiling, to investigate the consequence of standing and breaking waves in interaction with the tank top.

Typical arrangement and configuration of hot-spot locations in numerical sloshing model is displayed on Fig.22.

5.5 Results

For each of analyzed cases, sloshing computation results are to be post-processed per hot-spot zone. The highest values of normal impact velocities with respect to the tanks boundaries and quasi-static forces (per square meter) are to be extracted together with reference time-instant of the impact. Moreover, fluid velocities and accelerations at the pump mast location are to be extracted.

5.5.1 Fluid normal velocities

For example, on Fig.23 and Fig.24 are depicted the envelope curves of the adimensionalized quasi-static pressure (kN/m2) and normal velocity as functions of the filling level for one particular project. As quasi-static pressures and normal velocities are higher along the side wall than along the transverse bulkhead (cofferdam), only side wall values are depicted.

One can notice that the most important values are obtained for filling ratios between [15%H: 20%H]. Regarding this project, this range of filling ratios was also identified as the most critical during the sloshing model tests campaign. This conclusion is a validation of the filling ratio considered in the sloshing model tests campaign.

5.5.2 Quasi-static pressure

The quasi-static pressure loads Pw (kN/m^2) obtained from sloshing calculations are to be applied for the inner hull strength assessment (see NI564, Sec 2, [2]). Example of such adimensionalized quasi-static pressure distribution envelope as a function of the filling level is given on Fig.23.

5.5.3 Fluid velocities and accelerations at pump mast location

Fluid velocities and accelerations et the pump mast location are to be extracted in order to evaluate hydrodynamic forces acting on this pump mast. However, for the pump mast strength assessment, other relevant elementary loads such as the inertia forces due to vessels' motion, gravity, thermal loads, pump torque effects are to be also taken into account as explained in NI564, Appendix 1.

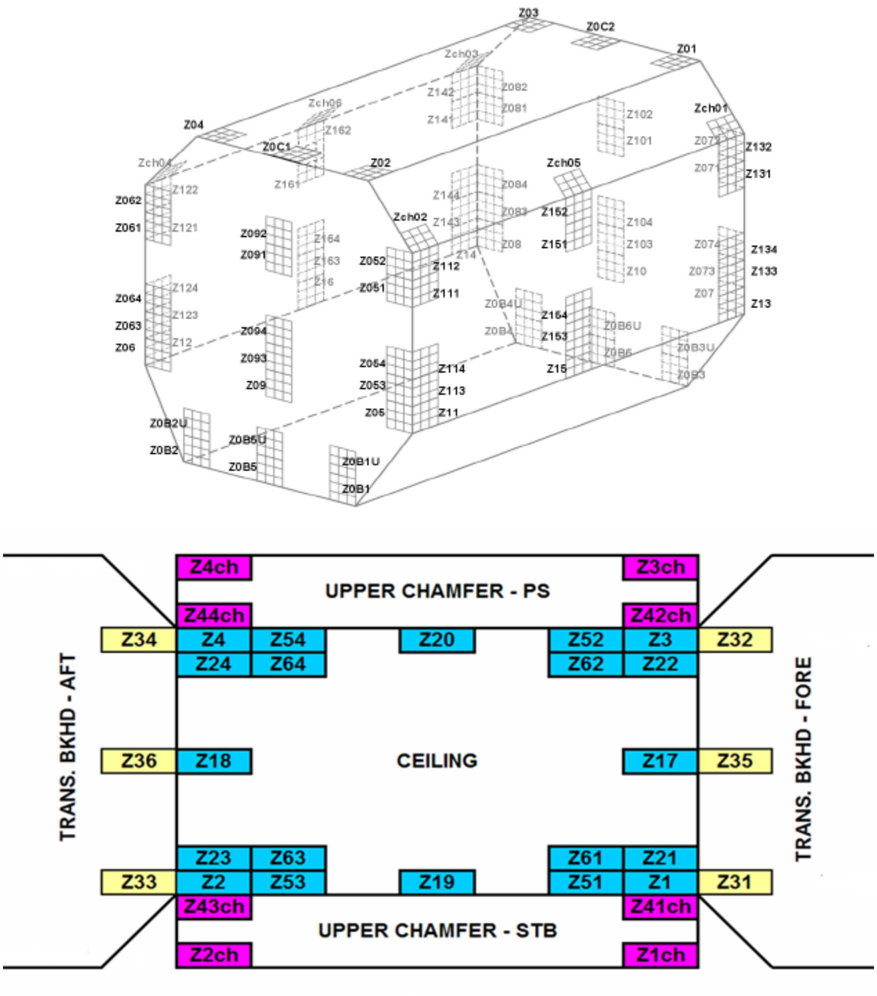

Figure 22: Typical configuration of hot-spot zones locations: General arrangement (top left), Ceiling (top right), Transverse Bulkhead (bottom left) and Sidewall (bottom right)

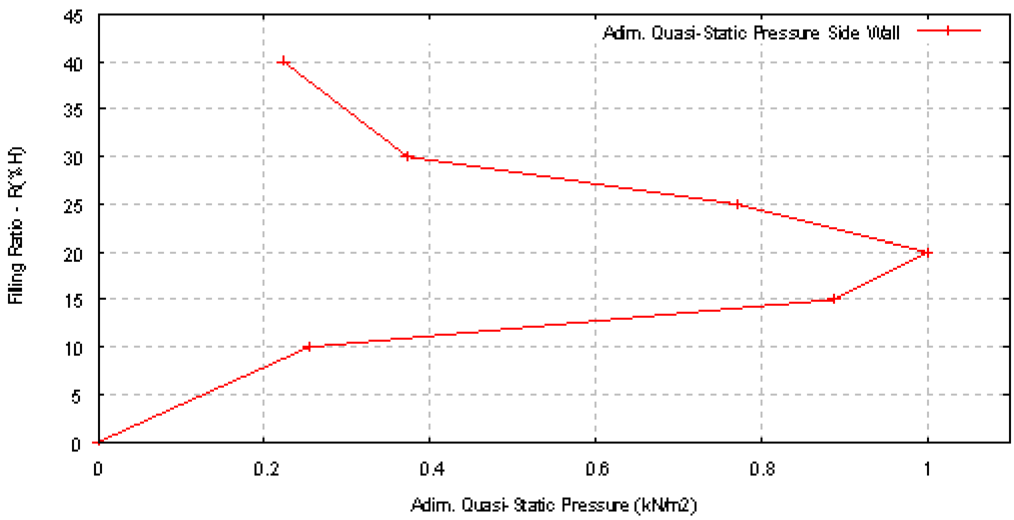

Figure 23: Example of adimensionalized quasi-static pressure as a function of the filling level

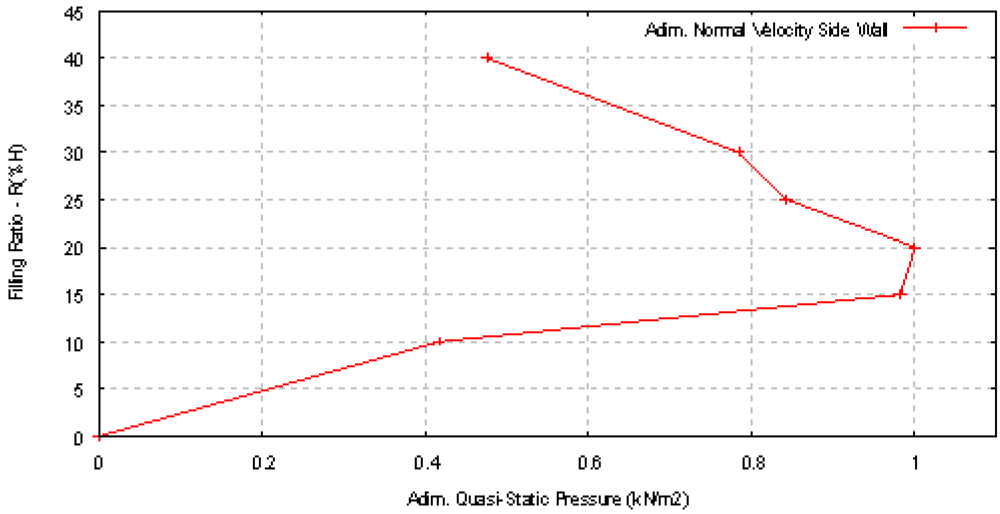

Figure 24: Example of adimensionalized normal velocity as a function of the filling level

6. Sloshing model tests

Sloshing small-scale model tests are standard part of the Society comprehensive sloshing assessment. Model tests facilities, test program, methodology, procedure and results have to be submitted to the Society for review and approval.

As a general statement, sloshing model tests should be driven by 6 degrees of freedom motion generator to describe realistic ship motion, hence realistic fluid flow inside tanks.

Due consideration is given to the following relevant model test features and parameters, including:

- Model test facility features: degrees of freedom and capacity of motion generator, model scale, tank model material, specification, location and arrangements of pressure sensors, test liquid characteristics, gas/liquid density ratios, ullage effects, data acquisition system
- Selection of relevant tank fillings. Selection of representative test cases: type and nature of liquid flow expected to be induced, specification of forced excitation associated to the selected tank fillings
- Description of data analysis: filtering and statistical post-processing of the measured data
- Model test results: pressure time-history, maximum measured and statistical values of model scale impact pressures, impact location and sample size

6.1 Test rig and motion generation

The test rig should be capable to reproduce the 6 degrees of freedom motions of the ship predicted by the seakeeping analysis [4] at the desired scale [6.2].

Due attention has to be paid on the accuracy of the reproduction of the 6 degrees of freedom motions for all the fillings. Thus, maximum allowable errors are to be less than 0,5 mm in translational modes and 0,1 degree in rotational modes.

Tank excitations at the desired scale are derived from the motions at full scale (see [4.5]) by means of the Froude similitude.

6.2 Tank Model

The tank model is to be geometrically similar to the studied tank. The scale is not to be less than 1:50.

The tank is to be enough rigid in order to be considered as rigid with respect to the measured loads. The model-scale tank design is to be equipped with flexible pressure sensors modules for easy instrumentation at various locations. Moreover for the flow visualization, the tank model is to be transparent.

In case of heavy ullage gas, the small scale model tank is to be tight and equipped with a proper pressure relief mechanism (when the heavy gas is slightly over pressured).

6.3 Liquid and ullage gas

Water is usually used as liquid in sloshing model tests.

Through both mathematical formulations and physical tests, it is shown that ullage gas has a great influence on maximum pressures during sloshing impacts. It is recommended to conserve the ratio densities between the gas and the liquid at model and full scales:

$$\frac{\rho_{Ullage\,Gas}^{Ambient\,Tempertaure}}{\rho_{Water}^{Ambient\,Temperature}} = \frac{\rho_{Methane}^{-160°C}}{\rho_{LNG}^{-160°C}}$$

However, since this present sloshing assessment procedure relies on a comparative approach, it may be considered a ullage gas which does not fulfill the above density ratio relation. For example, air may be considered as ullage gas for sloshing model tests.

The liquid and ullage gas selection is to be discussed and agreed with Society.

6.4 Sensors

The characteristics of the pressure sensors are to be chosen accordingly to the expected pressure magnitude, rise time and spatial resolution. The minimum pressure sensors sampling rate is to be equal to 20 kHz in order to properly capture pressure peaks and time histories. The magnitude range is to be chosen accordingly with model scale. However, a minimum range of 5 bars is required. The pressure sensor diameter should be small enough in order to get a minimum of 4 pressure sensors for the equivalent surface of $1m^2$ at full scale. Finally, the natural frequency of the pressure sensor is to be out of the range of sloshing impact dynamics in order to avoid any interaction between impact phenomena.

The pressure sensors characteristics supplied by the manufacturer are to be agreed by the Society before the beginning of the model test campaign.

These pressure sensors are also to be checked during the test campaign. Thus, some tie back tests are to be performed (for instance every two days) and obtained pressures compared to the original ones in order to check measurement consistency. If the deviation is too high, the pressure sensor is to be rejected.

One other way to assess the pressure sensor is to carry out drop tests. This experiment consists in dropping one wedge equipped with pressure sensors on a liquid surface at rest. For wedges with dead-rise angles greater than 5°, Wagner's solution for pressure is proved to be satisfactory. Thus, several tests for the same heights and at different heights can be carried out and the measured time pressure histories can be compared to the Wagner's reference solution. If the deviation is too high, the pressure sensor should be rejected.

Since sloshing pressures as a function of the loaded area are required for the strength assessment, all the pressure sensors within one sensor array are to be synchronized in order to reconstruct the pressure time history over any sub-area inside this sensor array.

6.5 Sensors arrangement

The sensors arrangement is this one used for CFD calculations [5.4.2].

6.6 Video recording

Short standard video recordings may be recommended for each test in order to have an idea of the global flow inside the tanks and validate the position of the pressure sensors.

Moreover, some high speed video recordings may be used in order to study more in details some impacts. Usually, this kind of video camera requires intensive light provided by powerful lamps. Due attention is to drawn on the heating of these lamps which could distort the pressure measurements.

6.7 Global forces measurement

In order to validate the coupled hydrodynamic analysis between seakeeping and sloshing, it may be required to measure global forces exerted by the fluid on the tanks boundaries.

The characteristics of the measurement device used for global forces measurement are to be chosen accordingly to the expected global forces magnitude and time resolution. The minimum sampling rate is to be equal to 100 Hz. The magnitude range is to be chosen accordingly with model scale.

Based on this global forces time histories, transfer functions for each degree of freedom can be derived and compared to the transfer functions calculated by the hydrodynamic analysis. If an important deviation is obtained, then the hydrodynamic analysis should be rejected and performed again using a more refined model.

6.8 Data processing of impact pressures

Depending on the pressure sensor characteristics (see [6.4]), pressure results can include noise, hydrostatic pressure, low (wave) frequency fluid oscillations and high frequency sloshing impact pressures. Only high frequency impact pressures are of interest. Thus, a high pass filter of 4 Hz is to be used in order to eliminate hydrostatic pressure (if any) and low (wave) frequency fluid oscillations. This filtered signal is to be used for the subsequent numerical analysis. Indeed, working on the raw signal and on the possible slow drift that it may contain could lead to erroneous statistical post-processing.

Then, a peak over threshold method is to be used to extract the pressure maxima and rise times for different loaded areas [6.4]. The threshold value should be set from one hand low enough in order to keep all significant sloshing impacts and on the other hand high enough in order to eliminate noise in order to avoid bias in the statistics..

6.9 Load Area Processing

The response of the structure depends on the loaded area, i.e. the area impacted by the fluid, and therefore it depends on the pressure distribution in this impacted area [6.4].

Therefore, the sloshing loads for all sensors combinations (Fig 25) are to be post-processed in order to derive sloshing pressures as a function of the loaded area. The pressure is logically a decreasing function of the loaded area.

For each panel of pressure sensors, different set of sensors can be extracted, corresponding to different values:

- 9 sets of single sensor: $\{Pij\}_{i,j=1,2,3}$
- 6 sets corresponding to 3-by-1 and 1-by-3 sensors areas
- 4 sets corresponding to 2-by-2 sensors areas
- 4 sets corresponding to 3-by-2 and 2-by-3 sensors areas
- 1 set corresponding to the whole panel (3-by-3 sensors area).

The load area post-processing is to be carried out during the screening phase and could lead to different (depending on the loaded area) critical cases for the design phase. All these critical cases are to be studied.

As explained [6.4], all sensors are synchronized in order to reconstruct pressure time history over all sensor arrays. Based on this pressure time history, all pressure time histories over any sub-area can be derived. All these time pressure histories are post-processed in the same manner as pressure time history for one pressure sensor.

6.10 Scaling law

Due to the complexity of sloshing phenomenon, it is impossible to identify a unique scaling law which can extrapolate sloshing pressures from model to full scale. This is the reason why the sloshing assessment procedure is based on comparative assessment. The details of this comparative assessment are given in [7.5] and in NI564 “Strength Assessment of LNG Membrane Tanks under Sloshing Loads”, Sec 3, [5.3].

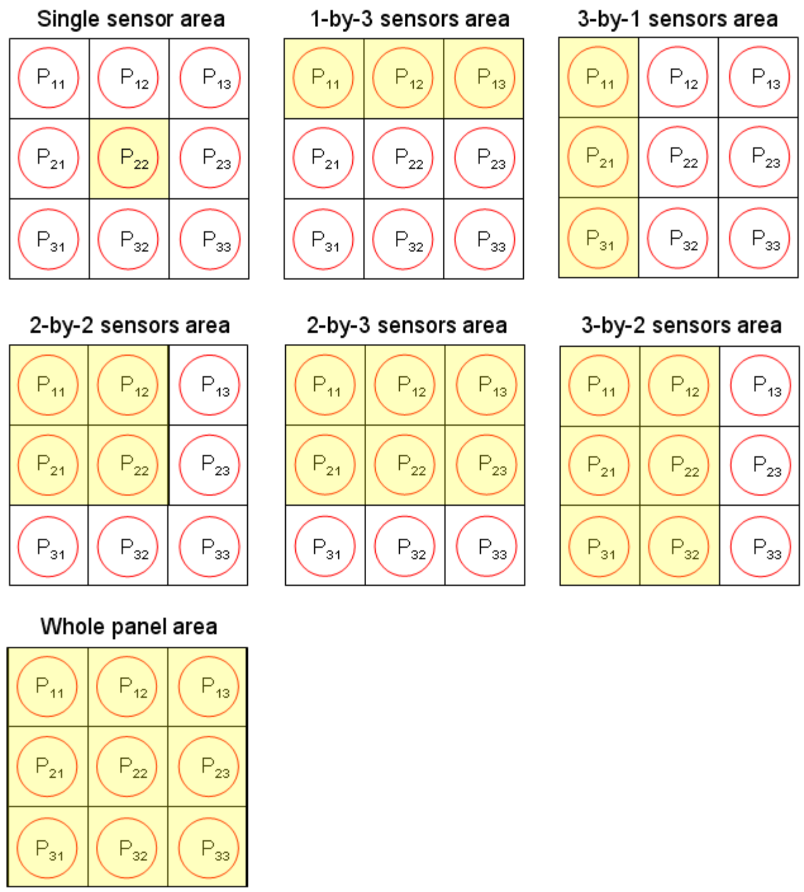

Figure 25: Sensors arrangement for load area processing

7. Sloshing model tests statistical post-processing

7.1 Statistical post-processing

7.1.1 Statistical fitting distributions

Pressure peaks (obtained by the peak over threshold method [6.8]) corresponding to each navigation condition and each loaded area [6.9] are to be statistically post-processed as described hereafter.

Different statistical fitting distributions should be applied on the pressure samples recorded during the tests in order to identify this one which fits the best the recorded data. The fitting statistical distributions to be investigated are the Generalized Pareto distribution, the 3 parameter Weibull distribution, the Generalized extreme value distribution.

The parameters estimation of each fitting distribution is to be discussed and agreed with the Society.

The selection of the statistical distribution which fits the best the samples data is to be justified by the use of statistical tests of goodness of fits such as Kolmogorov Smirnov test. The selection of the statistical tests of goodness of fits is to be discussed and agreed with the Society.

The present Guidance Note recommends the Generalized Pareto distribution as fitting statistical distribution (see Annex 1, D: “Fillon”) unless statistical tests of goodness of fits show the contrary.

7.1.2 Confidence intervals

Due to the size limit of the sample, parameters estimation is not exact, but remains random. From designer point of view, punctual estimation is meaningless. A safety margin corresponding to the risk acceptance of the underestimating load pressure is provided by the confidence intervals.

Confidence intervals are calculated using a bootstrap percentile method. This method consists in generating N samples called bootstrap samples, from the initial sample using a random drawing with replacement. Thus, it is possible to obtain similar observations in a bootstrap sample. N bootstrap samples are the same size as the initial sample. Afterward, each of these N samples is fitted by a probability distribution. The bounds of the confidence interval are directly obtained from these fittings for the desired confidence level.

7.1.3 Example

The above statistical post-processing is here illustrated on Fig.26 and Fig.27 for the Generalized Pareto, 3-parameter Weibull and Generalized extreme value distributions for sample data associated to one loaded area and one navigation condition (Hs, Tp, relative wave heading and filling level). The x-axis and y-axis represent respectively pressure values in mbars and its associated exceedance probability function (the probability that a certain pressure value is going to be exceeded). The sample data (peak impact pressures) is represented by blue dots. The three fitted exceedance probability functions are represented by a black curve (3 parameter Weibull), a red curve (Generalized Pareto distribution noted Gpa) and a green curve (Generalized extreme value distribution noted Gev). The 3 and 10 hour return periods are represented with a black horizontal line. On Fig.28-b, confidence intervals are also depicted for a 95% confidence level.

- First, one can notice that different statistical fitting distributions can lead to very different statistical pressures when return period increases. These differences emphasize the necessity to ensure a satisfactory fitting by using statistical tests of goodness of fit as mentioned in [7.1]. In this particular case, the Gpa distribution represents the best statistical fitting distribution for the sample data.
- Second, one can check the high variability of sloshing pressures with respect to the return period.
- Third, the confidence intervals width can be reduced by increasing test duration.

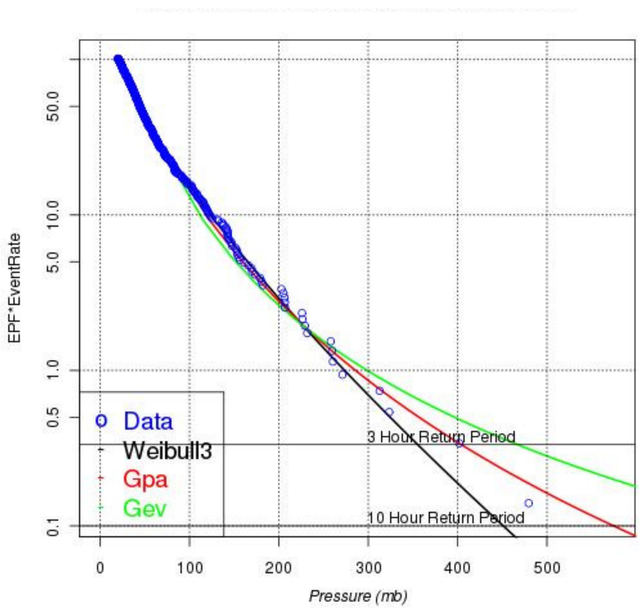

Figure 26: Results of the 3 fitting distributions for one test of five hour duration

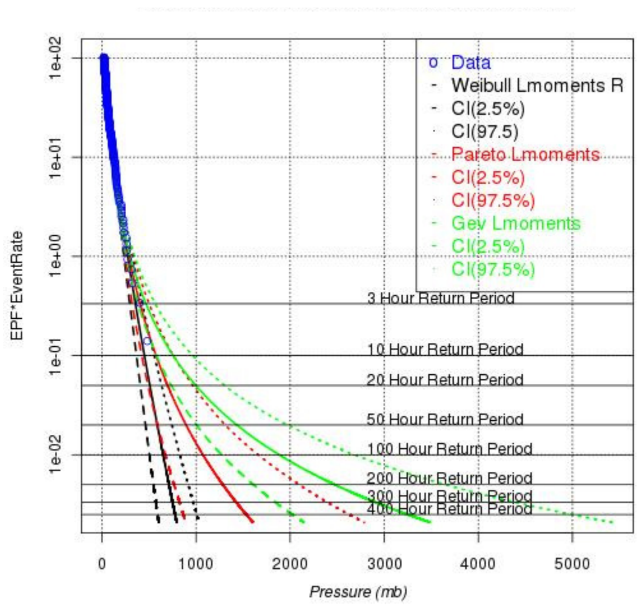

Figure 27: Sample fittings by a Gpa, 3-parameter Weibull and Gev distributions, confidence intervals and return periods.

7.2 Short Term Approach

The short term approach consists in determining the most critical condition (described by a combination *Hs – Tz –* heading and filling ratio) in terms of sloshing impact pressure and to determine the statistical pressure with a return period of 3 hour which corresponds to the duration of sea state.

The basic idea of the short term approach is to associate:

- a statistical law which fits the pressure sample data [7.1]. This statistical distribution associates to a given impact pressure the probability to exceed this pressure. This statistical law is called the short term exceedance probability function of sloshing impact peak pressure values, noted $Q_{ST}(p)$
- a number of impacts after a given number of hours spent in this sea state (usually 3 hours) defining the probability to be considered, noted N_{ST}.

Then the so called “short term” pressure can be calculated according the following formula:

$$Q_{ST}(p_{ST}) = \frac{1}{N_{ST}}$$

The design short term pressure is finally equal to the maximum short term pressure among all the sea states the ship will face during her lifetime. It is expected that design short term pressure [7.3] will be lower than the long term design pressure. However, this short term approach is relevant when considering emergency departures scenarios or when considering isolated extreme sea states (such as typhoons) not covered by the scatter diagram used in the long term approach scenario.

7.3 Long term Approach

Both observations of the few sloshing events which occurred at sea (see Annex 1, B “Gervaise”) and sloshing model tests (pressures do not repeat themselves even under same drive motions).clearly indicate variability of sloshing pressures. This stochastic behavior of sloshing pressures result in a flat tail exceeding probability curve. As a consequence, a small change in the probability level (i.e. return period) can have strong influence on the statistical pressure [7.1.3]. This is the reason why all navigation conditions associated with their expected return period (long term approach) are to be taken into account.

7.3.1 Operating scenario

Establishing the maximum expected pressures with a long term approach entails some hypothesis regarding the operating scenario. These assumptions of the operating scenario concern:

- the filling probability; the probability the ship will experience the filling range.
- the sea states encountered and their occurrence. The sea states and their expected return periods (based on environmental conditions) the ship will experience. Due to some possible filling level limitations, the considered sea states can depend on the filling range.
- the heading repartition: percentage of time the ship will spend at a given heading. As already mentioned for the wave heading analysis (see [4.3.2.1]), the heading repartition can depend on the sea state.

For the reference case, the operating scenario considers filling probability deduced from in service operations, the North Atlantic scatter diagram (IACS Rec. 34, Rev 1 June 2000) and an equiprobable distribution of the headings.

For the target ship, the operating scenario has to consider conservative assumptions. These assumptions are to be discussed and agreed with the Society.

7.3.2 Long term EPF per sea state

Thus, the basic idea of the long term approach is to associate to each one of the sailing condition the ship will face during its lifetime:

- the short term exceedance probability function of sloshing impact peak pressure values, noted $Q_{ST}(p)$ corresponding to the sailing condition
- a probability of occurrence for this sailing condition

Then the contribution of the all the sailing conditions can be cumulated together, which results in a long term probability of exceedance.

Regarding mathematical formulation, the present Guidance note considers the following formulation for the long term exceedance probability function (per sea state):

$$Q_{LT}(p) = 1 - \sum_{1}^{N_{SL}} \alpha_i \left(1 - Q_{ST_i}(p)\right)^{3*ER(i)}$$

$Q_{LT}(p)$ Long term exceedance probability function (per sea state)
p Sloshing peak impact pressure
N_{SL} Total number of sailing conditions
α_i Sailing condition probability
$Q_{STi}(p)$ Short term exceedance probability function of the ith sailing condition
$ER(i)$ Events rate for the i^{th} sailing condition (i.e. number of peak impact pressures per hour)

7.3.3 Long term EPF for a T hour return period

The long term exceeding probability function associated with a T hour return period $Q_{LT}(p,T)$ is calculated as follows. A Bernoulli scheme is applied to the sea state cumulative density function of the load, $F_{LT}(p)$ at the considered return period T. The T hour return period corresponds to T/3 sailing conditions assuming that a sailing condition lasts 3 hours.

$$F_{LT}(p,T) = (1 - Q_{LT}(p))^{T/3}$$

$$Q_{LT}(p,T) = 1 - (1 - Q_{LT}(p))^{T/3} = 1 - \left[\sum_{1}^{N_{SL}} \alpha_i \left(1 - Q_{ST_i}(p)\right)^{3*ER(i)}\right]^{T/3}$$

The long term probability density function of the sloshing loads (associated with a T hour return period) $f_{LT}(p,T)$ is obtained by derivation of the long term exceedance probability function of the sloshing loads at the considered return period (T hour) $F_{LT}(p,T)$.

7.4 Rise time

Sloshing impacts are a highly dynamic phenomenon. The crucial parameters to describe the dynamic characteristic of an impact pressure are the rise time and decay times defined in Fig. 28:

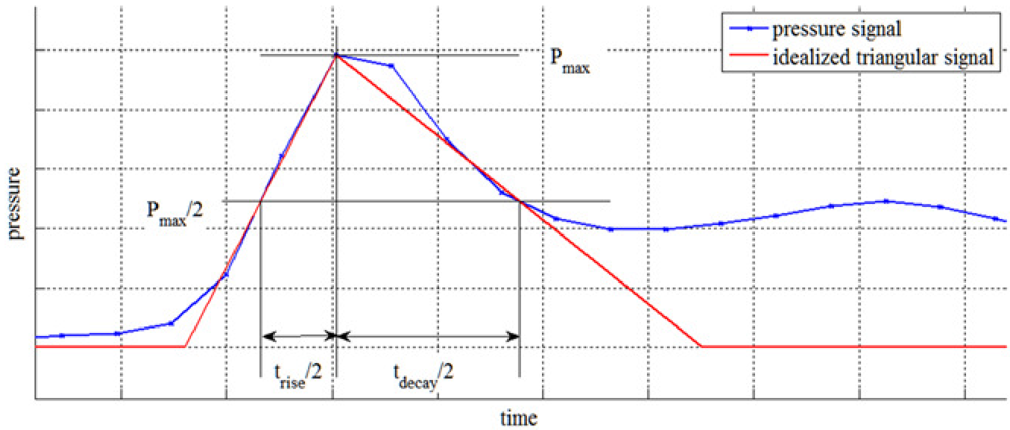

Figure 28: rise and decay times definition

Then the measured rise and decay times from small-scale model tests should be scaled up to full scale. Froude similitude is generally considered as appropriate for sloshing impacts. However, other scaling laws may be considered.

The rise and decay times scaling law is to be discussed and agreed with the Society.

7.5 Comparative assessment

At this stage of the sloshing loads assessment procedure, the curves giving the following design loads for reference and target vessels, as functions of the loaded areas and the considered return period are known:

- P_{ref} : Design sloshing loads for the reference vessel – measured from small-scale model tests.
- P_{target} : Design sloshing loads for the target vessel – measured from small-scale model tests.

The evaluation of the curves (as functions of the loaded surfaces) giving the structural capacities for the reference and target vessels is given in NI564 "Strength Assessment of LNG Membrane Tanks under Sloshing Loads".

The reference vessel is used to determine the scaling factor λ from small scale to full scale. The reference vessel is considered having not encountered any damage, so its scaled design load curve is necessarily below its capacity curve. The λ factor is chosen so that the scaled design load curve of the reference vessel is tangent to the corresponding capacity curve, as show in Fig.29. Therefore, it can be expressed as:

$$\lambda = \min\left(\frac{C_{ref}}{P_{ref}}\right)$$

Finally, to assess the target vessel, the small scale design loads are scaled by the factor λ obtained previously and by a safety factor *SF* (taking into account the long term confidence intervals), and compared to the capacity of the target vessel, as shown in Fig.30. This assessment could be summarized by the following formula:

$$C_{target} \geq SF\ \lambda\ P_{target}$$

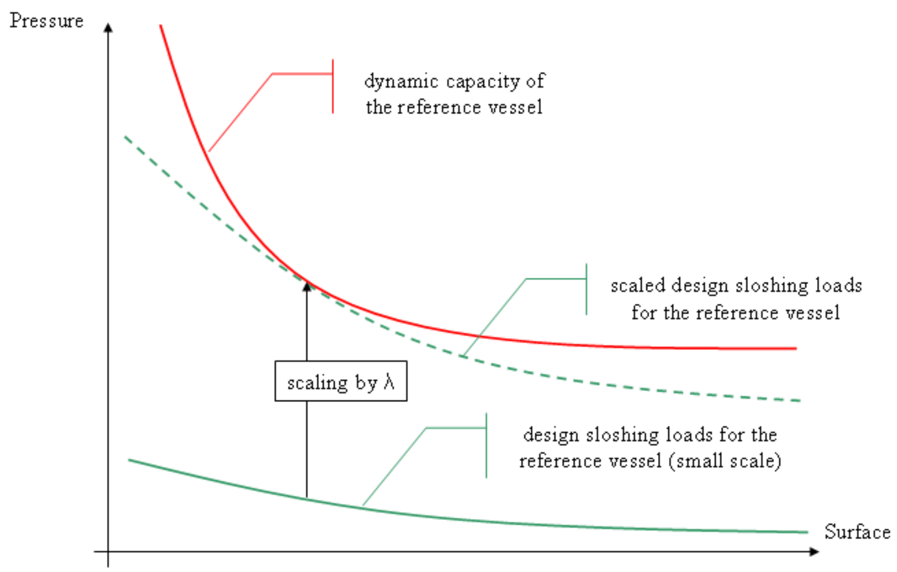

Figure 29: Comparative strength assessment – step 1.

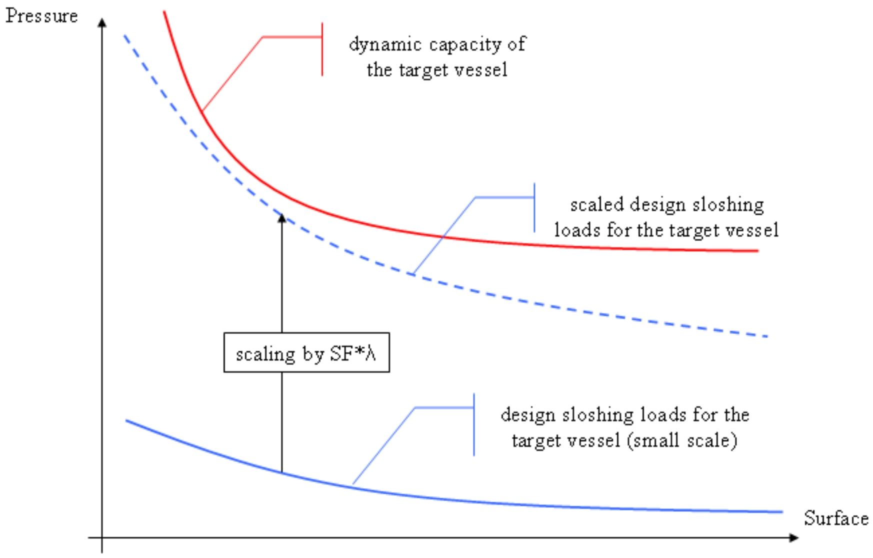

Figure 30: Comparative strength assessment – step 2

Annex 1

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Achevé d’imprimer sur les presses d’Activ’Company
77 bd Exelmans - 75016 Paris (France)
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