TÜRK LOYDU

TECHNICAL CIRCULAR

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Related Requirement : TL CSR Part 1, Chapter 4, Section 6, 6.1.2; TL CSR Part 1, Chapter 10, Section 4, 1.3.7.

Subject : Guidelines for the Assessment of Sloshing Impact Loads

Entry into Force Date : 01.07.2020

The following guidelines are used where sloshing impact assessment required for tanks with a maximum effective sloshing breadth, greater than 0.56 B or a maximum effective sloshing length, l_{slh}, greater than 0.13 L at any filling level from 0.05 h_{max} to 0.95 h_{max}.

TÜRK LOYDU

Guidelines for the Assessment of Sloshing Impact Loads

July 2020

This latest edition incorporates all rule changes. The latest revisions are shown with a vertical line. The section title is framed if the section is revised completely. Changes after the publication of the rule are written in red colour.

Unless otherwise specified, these Rules apply to ships for which the date of contract for construction as defined in TL- PR 29 is on or after 1st of July 2020. New rules or amendments entering into force after the date of contract for construction are to be applied if required by those rules. See Rule Change Notices on TL website for details.

"General Terms and Conditions" of the respective latest edition will be applicable (see Rules for Classification and Surveys).

If there is a difference between the rules in English and in Turkish, the rule in English is to be considered as valid. This publication is available in print and electronic pdf version.

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Guidelines for the Assessment of Sloshing Impact Loads

SECTION 1

GENERAL

Page

A. Application

1. These Guidelines define the calculation procedure for the sloshing impact assessment when tanks dimensions are outside the range as defined in TL CSR Part 1, Chapter 4, Section 6 [6.1.2] and TL CSR Part 1, Chapter 10, Section 4, 1.3.7.

"For tanks with a maximum effective sloshing breadth, b_{slh}, greater than 0.56 B or a maximum effective sloshing length, l_{slh}, greater than 0.13 L at any filling level from 0.05 hmax to 0.95 hmax"

2. These Guidelines are to be used in conjunction with other requirements defined in **TL** CSR Rules.

3 These guidelines may be applied for the calculation of design sloshing loads of cargo tanks of LNG Carriers.

4. These guidelines set out an assessment methodology and recommendations for the assessment of sloshing loads, if an alternate or different methodology is used by the designer, it should be consulted with **TL** from beginning of the design phase for the acceptance.

B. Symbols and Abbrevations

1. The main symbols and abbreviations used throughout in these guidelines are given below:

- H: Tank depth,
- Hs : Significant wave height,
- Vmax : Maximum service speed,
- Vs : Service speed,
- CFD: Computational Fluid Dynamics,
- LNG: Liquefied Natural Gas,
- RAO: Response Amplitude Operators.
- TL CSR: Common Structural Rules for Bulk Carriers and Oil Tankers.

C. Documents to be Submitted

1. Following data is to be documented and submitted to **TL**:

- Type, size and capacity of the vessel,
- Service speed,
- General tank arrangement,
- Tank geometry and proportions,
- Tank filling levels with reference to loading plan,
- Hull geometry of the vessel,
- Weight distribution and inertia characteristics of the vessel,

- Heave, pitch and roll natural periods of the ship at given loading conditions,
- Wave heading, spectrum and wave scatter diagram,
- Model experiment set-up including degree of freedom, data acquisition and statistical processing procedure,
- Model scale, model geometry and material,
- Arrangement, location and calibration records of pressure sensors,

2. **TL** reserves the right to request the submission of additional data or documentation if it is deemed necessary.

SECTION 2

SLOSHING ASSESSMENT METHODOLOGY

A. INTRODUCTION

1. General

This guideline is prepared for the assessment of sloshing impact assessment of double hull oil tankers with large tanks. However, in current market and design practice, gas carriers are mostly experience violent sloshing loads. This is because of modifications to traditional LNG trades due to FPSO/FSRUs and their shuttle vessels. To take into account these new trades and the related specific operating conditions, LNG carriers and FPSO/FSRUs have to allow partial filling levels in their tanks.

Results given by studies on liquid motion in LNG tanks made for FPSO and FSRU allowed for a better understanding of the phenomenon encountered in partial fillings in membrane tanks. Complementary studies have been made for LNG vessels with a capacity of 138,100 m3 and more. The results of these studies show that partial fillings are acceptable in membrane tanks. This additional flexibility given to membrane LNG carriers allows for transportation of any cargo volume up to the maximum vessel capacity. Tank partial loading are now more and more needed on board LNG Carriers due to present and future markets. In current trade, some membrane LNG carriers can already be operated without any filling limitation.

Another reason for experiencing such sloshing loads is the arrangement of the gas carrier’s cargo tanks with four tanks in general. It is common design practice to assume that tank length is accepted up to 17% of ship length between perpendiculars and the tank breadth is extended across the port and starboard inner hull structures (~85 % of ship breadth). Tanks are also designed as octagonal with top and lower chamfers in general for the membrane type LNG Carriers.

In light of above, the sloshing assessment procedure and the details of the application will be detailed on samples on Gas Carriers throughout in this guideline.

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. The liquid in the partially filled tank can be subjected to violent sloshing due to the multi-degree motions. The rising sloshing wave hits the tank walls, generating a high impulsive load on the tank. In turn, the sloshing induced impulsive load can affect the ship motions. When the frequency of the external excitation is close to natural frequency of the tank, the impulsive load increases significantly. Therefore, studying the sloshing phenomenon and predicting its impact load are very significant for the structural design of the tank and the safe operation of the ship because of the risks involved with the structural damage of the containment structures and loss of stability.

Both the experimental research and analytical approaches are common techniques for the liquid sloshing study. To study complicated sloshing phenomena, experiments have always been a reliable and useful tool, but it requires excessive time and cost to conduct such experiments. In recent years, the computational fluid dynamics (CFD) techniques solving Navier Stokes (N-S) equations have become increasingly popular, due to the rapid development of computer technology and numerical algorithms.

B. ASSESSMENT PROCEDURE

The design sloshing loads are to be assessed by conducting a sloshing analysis taking into consideration the ship motions, tanks' geometry and filling levels inside the tanks for given density. The sloshing analysis is to be based on scaled sloshing model tests supported by CFD computations due to complexity of the problem. The recommended procedure for the sloshing load assessment is given in Figure 2.1.

The general assessment procedure for design sloshing loads is described in this section. In Section 3, ship motion analysis mentioned in the assessment procedure will be detailed with selection of tanks and test cases, cargo tank filling levels, ship's speed and loading conditions, and environmental conditions. In Section 4, the numerical simulation of violent sloshing by the CFD analysis will be presented. In Section 5, recommended model experiment set-up, data-processesing and post-processing of the results will be given.

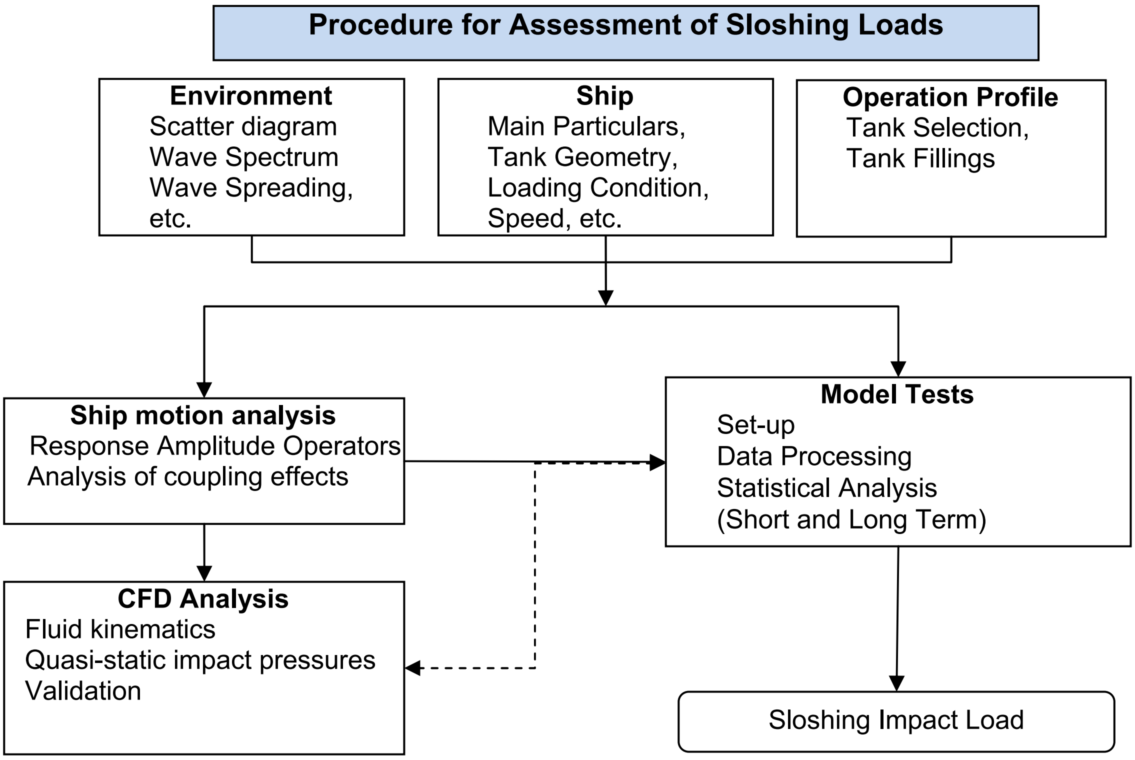

Figure 2.1. Sloshing Assessment Procedure

SECTION 3

SHIP MOTION ANALYSIS

Page

A. GENERAL

1. Aim and Purpose

Ship motion analysis is performed for calculation of the ship's motions. The sloshing excitation for the CFD and sloshing model tests will be determined as a result of this analysis.

2. Basic Information

The basic information and required inputs for the analysis will be detailed in below and will be used throughout in these guidelines.

2.1 Operation Profile

2.1.1 Selection of Tank

The selection of tank for the sloshing analysis is an important initial step and an input for all analysis performed in these guidelines. The tank is to be selected based on the arrangement and centre of gravity of the tank, tank geometry, and filling levels of the tank. In general, one of the tanks will be critical, however due consideration is to be given for combined multi-tank sloshing effects. The selection of the tank is therefore to be decided in early stages in consultation with **TL**.

2.1.2 Tank Filling Levels

Filling levels of the tank is to be based on operational of the vessel (loading and unloading) and to be selected by the designer. Standard filling levels are generally defined as 10%H, 70%H, 80%H, 90%H, 95%H. Where partial filling of the tanks are required, following filling levels are to be evaluated 15%H, 20%H, 25%H, 30%H, 40%H, 50%H, 60%H).

2.2 Ship Data

2.2.1 Hull Geometry

Main particulars of the ship, center of gravity, gyration radii, and suitable hull geometry should be provided as an input. If the hydrodynamic computation is to be based on 3D potential theory, the panel representation of the hull is to be provided (2000 quadrilateral/triangular panels). For the 2D strip theory based calculations the ship's hull is represented by two dimensional sections. Minimum 20 sections and 20 offsets for each section are required for a proper representation of ship hull form (Figure 3.1).

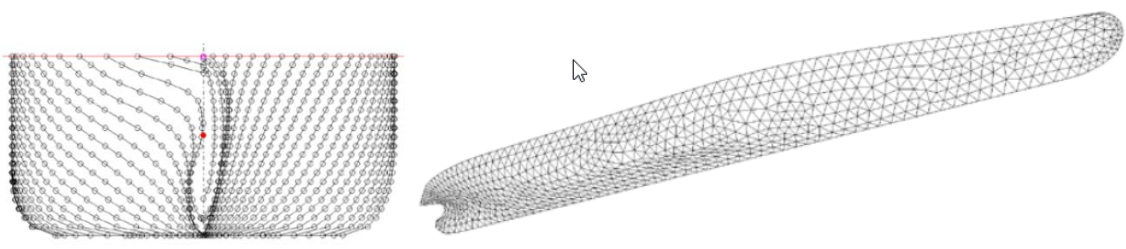

Figure 3.1 Typical hull form representations for 2D strip theory and 3D panel diffraction/radiation based calculations

2.2.2 Loading Conditions

The loading conditions are to be based on the conditions in the loading manual and should reflect the most representative ship motions for the determination of the ship motions for the sloshing analyses. For lower filling levels (< 10% H), the ballast condition and for higher filling ratios (> 70 % H), full load condition is generally to be studied. For partial filling, the coupling of ship and tank motion is to be considered for the selection of the loading condition. Following input data must be provided for selected loading conditions :

- main dimensions of the vessel, including the length, breadth, draught and depth,
- body plan and offsets including length between aft and forward perpendiculars, width and drafts,
- displacement, form coefficients, and centre of buoyancy,
- ship's weight and inertia characteristics described by the coordinates of the center of gravity and gyration radii,
- heave, pitch and roll natural periods of the ship.

2.2.3 Speed

The speed of the vessel should reflect typical operating speed. The speed of the vessel used in the analysis has an important effect on the sloshing loads. The ship speed depends on the sea state wave height and the relative wave heading between the prevailing incoming wave direction and the ship speed. A guidance for the determination of ship speed is given in Table 3.1.

Table 3.1 Ship speed definition as a function of wave height and heading

Wave height [m]	Heading				
	Following Seas	Quartering Seas	Beam Seas	Bow Seas	Head Seas
$\mathrm{H_S} < 5\,m$	$\mathrm{V_{max}}$				
$5\,m < H_S < 9\,m$	$\mathrm{V_{max}}/2$	5 knots			$\mathrm{V_{max}}/2$
$\mathrm{H_S} > 9\,m$	5 knots				

2.3 Environment

2.3.1 Wave Scatter

Environmental conditions to be provided for sloshing analysis are the description of wave data corresponding to the service specification. Long term wave conditions are derived by combination of a number of short term statistical distributions which shall be based on wave data corresponding to the service specification.

For vessels with world wide service conditions, Standard Wave Data (TL- G 34) diagram for North Atlantic trade route with significant wave height envelope fitted to 40-years return period shall be used for sloshing analysis as environmental data. The North Atlantic wave scatter diagram is presented in Table 3.2.

2.3.2 Wave Spectrum

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:

$$S(\omega) = \frac{A}{\omega^5} exp\left(-\frac{B}{\omega^4}\right)$$

with the significant wave height, H_S , used to specify the parameters A and B through the relationships

$$A = 0.0081g^2$$

$B = 0.032\frac{g^2}{H_S^2}$; where g is the gravitational acceleration.

Table 3.2 Standard Wave Data for North Atlantic

H_S/T_Z^*	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

For sea areas with limited fetch the following Bretschneider or two parameter Pierson-Moskowitz spectrum shall be used:

$$S(\omega) = \frac{H_S^2}{4\pi\omega^5}\left(\frac{2\pi}{T_Z}\right)^4 exp\left[-\frac{1}{\pi\omega^4}\left(\frac{2\pi}{T_Z}\right)^4\right]$$

T_Z : average zero up-crossing period (secs)

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

The assumption of short crested seas with an approved cosine spreading function spreading function may be applied. For the sloshing analysis calculations the response amplitude on the 1/10th level and the mean zero-crossing period are to be used.

$$R_{1/10} = 2.54\sqrt{m_0}$$

2.3.3 Wave Headings

A heading probability distribution taking into account the different environmental load actions at the specific site/route is to be performed. The number of headings to be considered should be sufficient to ensure a good representation of the actual operation of the vessel. In general, minimum of 15 degree steps for wave heading are recommended.

B. HYDRODYNAMIC ANALYSIS

1. Response Amplitude Operators

Response Amplitude Operators (RAO) or transfer functions represent the six degrees of freedom ship motion responses to the wave of unit amplitude as a function of ship speed, wave heading and wave frequency. The analysis of hydrodynamic loads and vessel motions is usually performed in the frequency domain using a potential theory based software. A 2D strip theory based software or a 3D panel diffraction/radiation based software may be used. This software shall be fully validated through the comparisons with semi-analytical studies, numerical results from recognized numerical tools and experimental results. As the roll motion of the ship in oblique waves is significantly affected by the hull and appendage viscous roll damping, the effect of viscosity should be properly taken into consideration.

For each loading case, hydrodynamic model is composed of the geometry of submerged part of the hull and of the corresponding weight distribution. The number of wave frequencies is generally between 50 to 70 covering the range of 0.2 rad/sec to 1.2 rad/sec in maximum increment of 0.05 rad/sec. A minimum wave heading step of 15 degrees is required. The predicted response amplitude operators shall include the following responses:

- motions, velocities and accelerations RAO at any point of the ship,
- wave kinematics to estimate relative motions, deck wetness and slamming occurrences,
- water added mass and damping matrices,
- dynamic pressures on the ship hull,
- wave induced global loads,
- wave induced loads at different ship sections.

It should be noted that at this stage the calculation of ship motion responses is based on regular waves of unit amplitude. The real ship motions in irregular seas are calculated by using the environmental data.

2. Short Term Spectral Responses

Short term spectral responses shall be calculated for each sea state likely to be encountered by using the following spectral moment formulation:

$$m_n = \int_0^\infty S(\omega)|RAO(\omega)|^2\,\omega^n d\omega$$

ω : Circular wave frequency (rad/sec)

$S(\omega)$: Wave energy density spectrum (m^2sec)

Short term distributions represent the statistical distribution of the sloshing impact load for a specific sea state, wave heading, tank filling, or any other environmental or operational parameter identified to be relevant for the assessment. It is recommended that the short term distributions are derived by statistical analyses of impact pressures recorded during sloshing model experiments or calculated by CFD analyses.

3. Coupling

In an irregular seaway the six degree of motions of a vessel carrying liquid cargo will cause a liquid flow in tanks which leads to the phenomenon called sloshing. In turn this internal liquid motion affects the wave-induced response of the vessel. However, in practical ship motion calculations the effect of the internal liquid motion is generally ignored. On the other hand, CFD based sloshing computations generally deal with one isolated tank submitted to the forced motion of the vessel for specific wave conditions.

In order to consider the effect of internal liquid on ship motions the seakeeping/sloshing should be included in the sloshing analysis by taken into account the following response frequencies:

- Natural frequencies of the vessel with no internal fluid motion for each response at specific wave conditions,
- Natural frequencies of the isolated tank in six degrees of freedom motions.

SECTION 4

CFD ANALYSIS

Page

A. GENERAL

1. Aim and Purpose

CFD analysis is performed for determination of fluid kinematics in the tanks and determination of sloshing impact loads for structural assessment of local structure inside the tank.

2. Introduction

The simulation of violent sloshing in is a challenging task, when the exciting frequency is close to the natural frequency of the liquid fluid. In the case of violent sloshing in a realistic LNG tank, part of the liquid–air interface may also break up into discontinuous droplets and small air bubbles. Both the experimental research (Kim et al, 2015; Akyildiz and Ünal, 2005) and analytical approaches (Faltinsen et al., 2000, 2001) are common techniques for the liquid sloshing study.

In recent years, the computational fluid dynamics (CFD) techniques have become increasingly popular, due to the rapid development of computer technology and numerical algorithms. The CFD techniques can be divided into grid-less and grid based methods (Atluri and Zhu, 2015). Altough the grid-less methods have great advantages in large deformation problems such as breaking waves, structural failure and violent sloshing flows (Cao et al., 2014; Daneshvar et al., 2017; Abbas et al., 2018), the enormous computational costs and algorithm complexities of the grid-less methods limit their wide applications. On the other hand, the grid based methods (Yang, 2016; Peng et al., 2019) have also been successfully applied to various sloshing cases such as LNG sloshing in a realistic ship (Bai et al., 2015), 3D liquid sloshing with baffles (Xue et al., 2012), and violent sloshing with breaking waves (Liu et al., 2017). In the grid based method, additional treatments are needed to track fluid-solid interface and capture fluid-gas interface.

For the successful simulation of violent sloshing, accurately tracking/capturing the free surface is critical because of the mass conservation of the sloshing fluid which directly affects the predicted impact pressure on the wall. To capture the highly nonlinear free surface, the LS (Level Set) method (Sussman et al., 1994) is one of the most widely used interface capturing schemes and has advantages in the geometrical representation of the interface and 3D implementation. To improve the mass conservation, some studies have been carried out (Sussman et al., 2000, Enright et al., 2002). Nave et al (2010) proposed a Gradient-Augmented Level Set (GALS) method, in which the LS distance function and its gradient information are evolved in a fully coupled way. Therefore, the sub-grid structure can be represented more realistically and the mass conservation can be better maintained. Lee et al., (2014) developed an incompressible two phase flow model based on the GALS method. Shi et al. (2019) developed a Cartesian grid based multiphase flow model to simulate water impact of a complex body.

Although the LNG tanks in most tankers have a non-rectangular prismatic form, in the most sloshing simulations, the tank is treated as the rectangular shape. Therefore, the boundary conditions can be easily enforced, because the computational grid is coincided with the tank boundaries. However, the liquid tank can be in various shapes such as prism and ellipsoid. To treat the sloping boundaries, the body-fitted grid technique is commonly used.

For example, Jiang et al. (2015) simulated the sloshing of two partially-filled prismatic tanks based on the OpenFOAM. Zhao and Chen (2015) simulated 3D sloshing flow in a partially filled LNG tank by the overset grid method. However, to handle multiple degree-of-freedom excitations or internal structures, the non-boundary-fitted method (Hou et al., 2012), where the governing equations are solved on a background Cartesian grid, provides an appealing alternative. In the non-boundary-fitted method, the body boundary does not coincide with the background grid lines. To treat the sloping boundaries for the irregular shape tank, Kim et al. (2004) introduced a concept of a buffer zone to enforce the free surface boundary conditions near the tank ceiling. To represent the existence of the baffles, Liu and Lin (2009) introduced a body force to the momentum equations by a direct forcing immersed boundary method. Lee et al. (2011) enforced a no-slip boundary condition on the body surface by a quadratic polynomial interpolation scheme. Ünal, et al. (2019) investigated the effective size of T-shaped baffles in a parametric study with varied baffle height, rotation angle, filling height using both finite differences and finite volume discretization techniques.

B. ANALYSIS

1. Computational Cases

The three-dimensional model of the tank should be prepared with high geometric accuracy. Filling levels should be selected according to Section 2 as minimum. No fewer than two degree-of-freedom (DOF) tank motions should be adopted for each computational case. For the calculation of the impact loads, two different wave induced tank motions should be modelled. In head sea conditions, the heaving and pitching motions should be adopted. In beam sea conditions, on the other hand, the heaving and rolling motions are to be considered.

A rotational motion around the axis that is perpendicular to the XZ plane and passing through the centre of floatation should be applied to the prismatic tank to induce the pitching motion. A fixed angular frequency should be chosen which corresponds to of the natural resonant frequency of the tank-liquid system for the liquid depths considered. The motion can be represented by a sinusoidal function $\theta = \theta_0 \sin(\omega t)$ where θ_0, ω and t imply imply rotation angle (amplitude), angular velocity and time, respectively. For the simulation of the rolling motion the method given above can be used. In this case the rotational motion should be introduced around the axis that is perpendicular to the XY plane. The heaving motion can also be described by a similar sinusoidal function. The heaving motion should be given in Z direction. The phase angles between the motions should be taken with great care and each motion should be started with zero velocity.

The theoretical formulations can be used for the determination of the resonant longitudinal and transversal frequencies, F_{xi}, F_{yi}, of prismatic tank, which depend on the filling ratio. The amplitude of each motion should be determined according to the ship motion analysis which should be carried out as a separate task. The maximum amplitudes in the extreme wave conditions found in that analysis shall be used in the sloshing simulations. As in these conditions the ship speed is very low, the sloshing motion can be modelled without taking the ship speed and hence the longitudinal tank motion into account.

The computational cases given in Table 4.1 are suggested for the determination of the impact loads for each filling ratio.

Table 4.1 Computational cases suggested

Case #	Filling ratio*	Direction	Amplitude	Frequency	DOF
xx	xx%	Head	Extreme	F_{xi}	Heave, pitch
xx		Beam	Extreme	F_{yi}	Heave, roll

**. Filling ratio is to be defined according to Section 2.*

To collect the pressure data on the tank wall in order to find the impact loads due the liquid sloshing motion, several numerical pressure sensors should be placed on the computational tank model. The number and location of the numerical pressure sensors should be determined depending on the shape of the geometry. A tank model along with the Cartesian coordinate system and sensor locations suggested can be seen in Figure 4.1

2. Numerical Approach

The liquid and gas in the tank should be assumed to be homogenous, incompressible, isotropic, viscous and Newtonian. The incompressible, unsteady Reynolds-Averaged-Navier-Stokes (RANS) equations can be used in the simulations. The calculation of the Reynolds stresses and the turbulence field may be preferably realised by means of the SST k-ω turbulence model of Menter (1994), or Realizable k-ε turbulence model (Shih et al., 1995) that are based on the Boussinesq hypothesis.

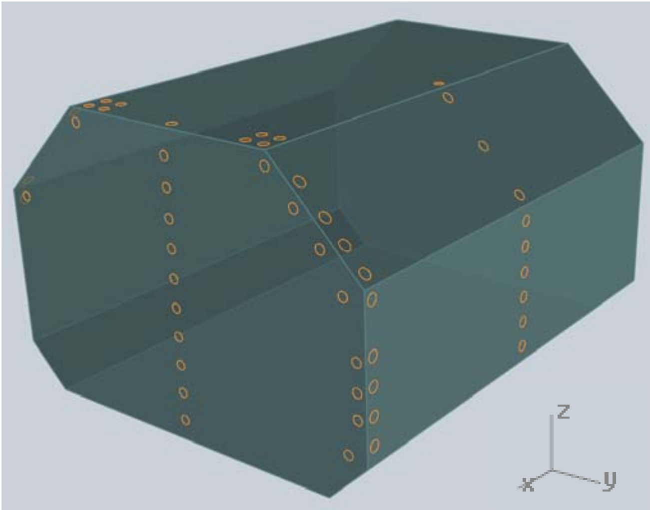

Figure 4.1 Tank model, pressure sensor locations and coordinate system

Finite-differences or fine-volume discretisation techniques can be employed to solve the RANS and turbulence transport equations. A pressure-based segregated algorithm can be applied for the solution. The evaluation of the gradients should be performed with node-based techniques. A SIMPLE-based velocity-pressure coupling pressure-correction method can be adopted. The pressure-staggering approach of Patankar and Spalding (1972) or body-force-weighted interpolation technique can be employed for the calculation of the pressure field. The use of the second-order central differencing is always suggested for the discretisation of the viscous terms. The spatial discretisation of the convective terms of the RANS and turbulent transport equations should be achieved with a second-order or third-order scheme (e.g. second-order upwind, third-order MUSCLE). The three-time-level implicit time-discretisation should be applied for unconditionally stable and accurate solutions.

The two-phase liquid and gas flows problem can be solved based on the Volume of Fluid (VOF) technique of Hirt and Nichols (1981). The tracking of the free surface should be performed with a high-accuracy second-order scheme. In order to increase the accuracy of the simulations, the maximum local Courant number in the flow field should be kept around 1. The pressure information should be collected at each time step of the analysis during at least 6 periods of pitching or rolling motion. The convergence of the solution at each time step was checked by the examination of the variation of the primitive variables, such as velocity and pressure, in addition to the scaled residuals of the equation systems.

3. Grid Generation and Verification

A H-type structured grid system should be preferred. The generation of highly skewed cells or high aspect ratios should be avoided. Grid Convergence Index (GCI) procedure of Roache (1998) should be followed with at least 3 different mesh systems by systematically varying the resolution at each direction. ITTC (1999) can be used as a guidance. The discretisation uncertainties of the average maximum and minimum pressure values should be specified as a result of the verification study. A view of an applicable mesh structures is given in Figure 4.2.

4. Validation

As the results of CFD Analysis may not be reliable, the validation of the CFD study should performed by comparing the numerical results with the pressure data obtained from the model tests. The model test results involving combined pitching and heaving motions and combined rolling and heaving motions with a filling ratio of 50% should be preferred. For the validation, the CFD study should be performed by introducing the amplitude and frequency of the individual ship motions observed in the model tests. For this purpose, rolling, pitching and heaving motions should be continuously measured during the model tests. The motion signals may be directly used in the CFD analyses or representative sinusoidal functions similar to that given in B.1 can be generated and employed in the simulations. Examples of the computed free surface deformations at different sloshing phases are given in Figure 4.4. The measured and calculated pressure signals at various sensor locations are also comparatively presented in Figure 4.5.

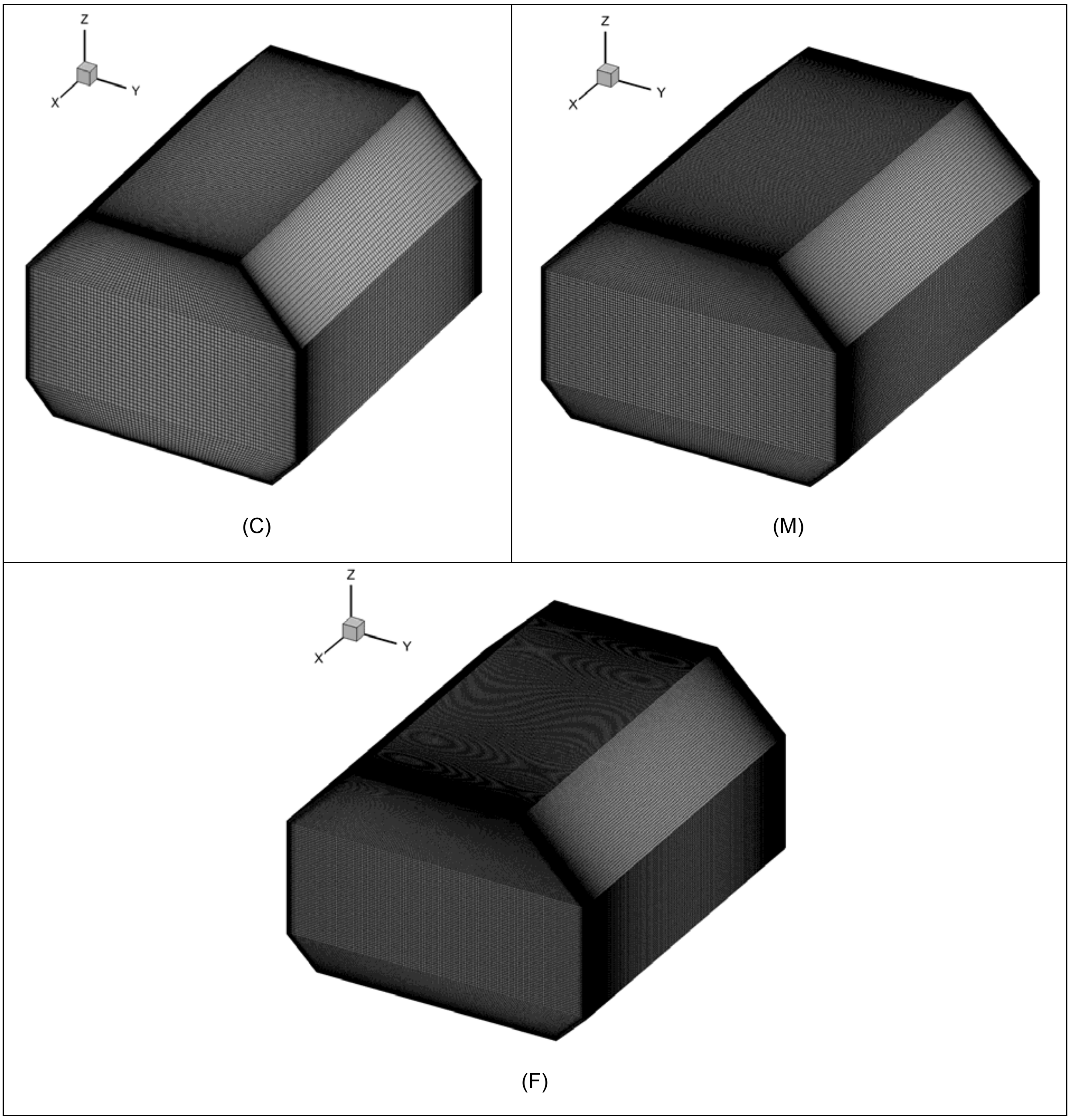

Figure 4.2 A view of the mesh structures: Course(C), Medium(M), Dense(F)

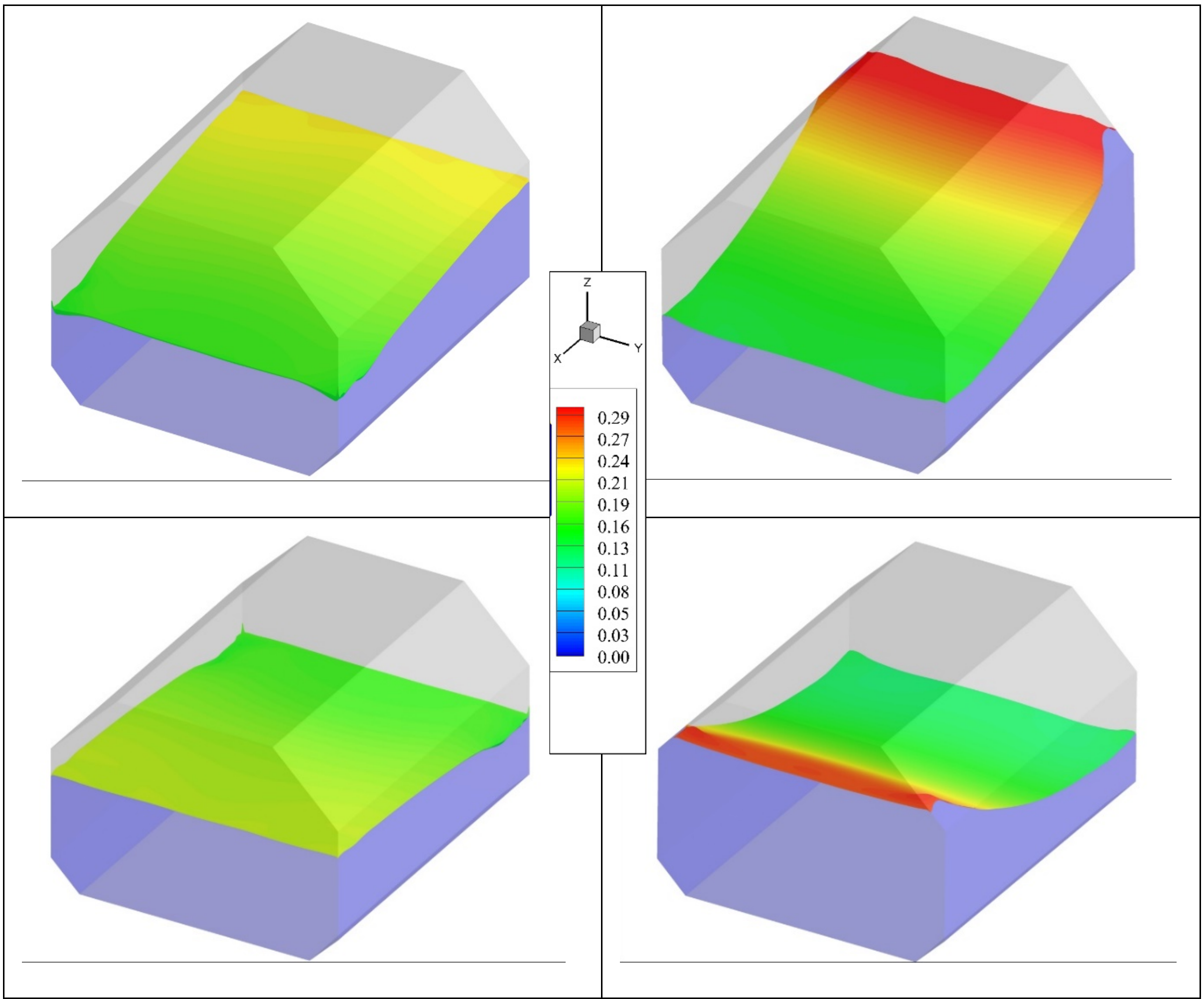

Figure 4.4 Free surface deformations at different sloshing phases ($t = \frac{T}{4}, t = \frac{T}{2}, t = \frac{3T}{4}, t = T$, in meters)

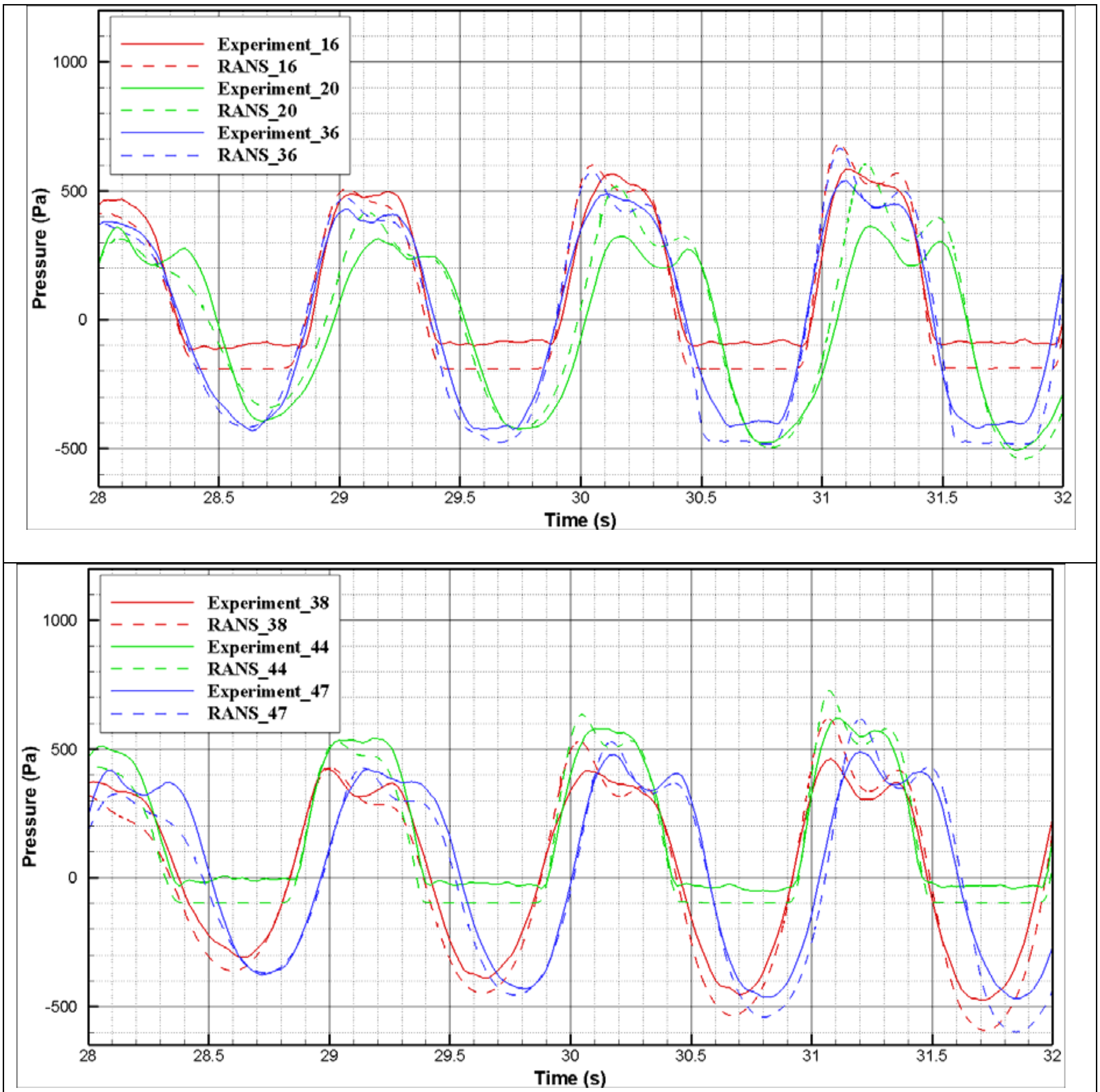

Figure 4.5 Measured and computed pressure signals at the sensors 16, 20, 36, 38, 44 and 47.

SECTION 5

MODEL TESTS

Page

A. GENERAL

Model tests aimed to simulate sloshing phenomenon in a scaled tank for the determination of sloshing impact load for the structural assessment. In particular, with model tests, impact pressure time series for short term statistical distributions were created and long term statistical distributions of the sloshing impact loads have been compiled by taking into account the operational environment.

As a general guidance, the ITTC Sloshing Model Tests procedure (7.5-02-07-02.7) is to be applied.

B. MODEL SETUP

Model tests are to be performed within a platform capable of simulating expected motions in all six degrees of freedom. Model tests with lesser degrees of freedom are to be agreed by **TL**. The tank model is to be as large as possible. The minimum scale of 1/50 is recommended. The tank is to be stiff enough to avoid interaction between sloshing load and natural frequency of the tank model. The tank is recommended to be made by transparent material (e.g. plexiglass) to observe the flow inside the tank (Figure 5.1).

Figure 5.1 Sample Tank Model

Measurement range and accuracy of the pressure sensors should be capable of capturing expected impact pressure loads. The sensors are to be calibrated for impact test. Drop test can be used for the calibration. Pressure sensors are to be allocated to capture the most critical impact loads with respect to filling ratios (e.g. corners). An example of pressure sensor distribution is provided in Figure 5.1 and 5.2.

C. MODEL TESTS

The test matrix is to be defined to allow derivation of long term distributions sufficiently. This may require large number of testing with changing parameters of filling levels, wave height, wave headings and sea state. Long model tests are needed to get reliable statistical distribution for pressures. The test programme can be composed of the determination of tank resonant frequencies for various filling and various leading motions, an identification of the category of the resonant mode (standing wave, travelling wave, etc.), harmonic tests with the leading motion only and harmonic tests with the leading motion and with possible other motions for respective measurement of pressures on the tank. Tank resonant frequency versus filling ratio curves of tank height may be first determined using the theoretical formulations for prismatic tank before model tests.

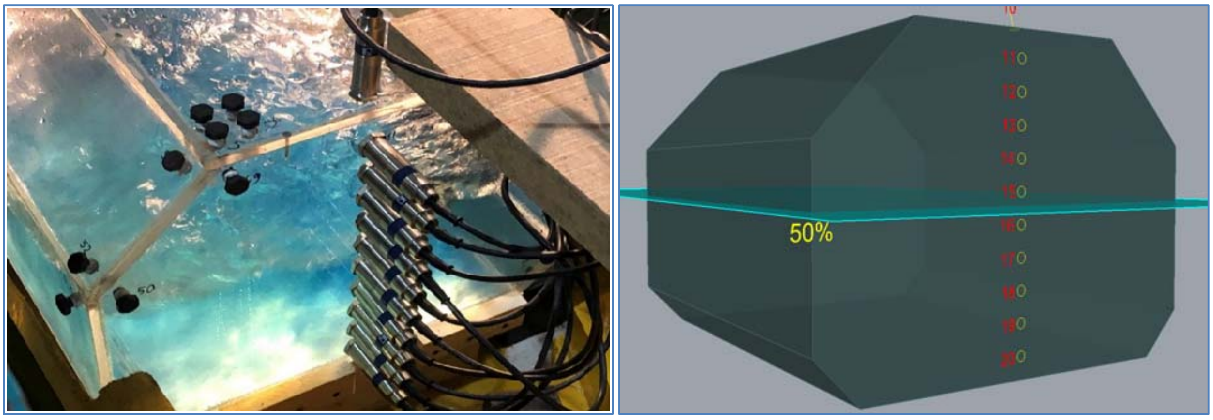

Figure 5.2. Sample Pressure Sensor Distribution

Longitudinal and transverse frequency for a rectangular tank can be determined by following equations:

- Resonant longitudinal frequency:

$$f_{xi} = \sqrt{\frac{g \tan\left(\pi \frac{h_i}{l_c}\right)}{4\pi l_c}}$$

- Resonant Transverse frequency:

$$f_{yi} = \sqrt{\frac{g \tan\left(\pi \frac{h_i}{b_i}\right)}{4\pi b_i}}$$

where;

h_i: liquid height (m)

l_c: length of free surface (m)

b_i: width of free surface (m)

Once the filling ratios selected (high, low or intermediate levels), the tests may begin by a frequency sweeping in order to get the resonant periods, then a recording of the impact pressures at these periods, with the maximum model tank motions. Longitudinal, transverse and diagonal directions have to be analysed for the case of tank resonant period. Steps for determination of the sloshing model test conditions may be summarised as follows:

- Step 1: Determination of resonance area
- Step 2: Determination of tank resonance curves
- Step 3: Selection of filling ratios *(See Section 3, A 2.1)*
- Step 4: Determination of wave frequency interval *(See Section 3, A 2.3)*
- Step 5: Determination of worst navigation conditions *(See Section 3, A, 2.3)*
- Step 6: Computation of ship's response *(See Section 3, B)*
- Step 7: Determination of tank liquid motion excitation

Sloshing impact pressures are to be measured during the test and raw data is to be saved for further analysis. Sloshing impact pressures can be combined by the average of pressure sensors in the impact area (1, 3x1, 2x2, 3x2, and 3x3 sensor distributions).

Dynamic chracteristics of sloshing impact load are represented by the pressure time histories, however it may also be simplified in triangular form by definition of the maximum pressure with rise and decay time.

Froude similarity can be used for the scaling of the time history of the sloshing pressure and tank motion to the full scale. Where the sloshing impact requires consideration of condensation, viscosity and other effects the scaling is to be agreed by **TL**. In this case, the sloshing impact load will generally be determined based on a comparative assessment with a reference design with proven service history.

D. STATISTICAL ANALYSIS

Sloshing impact pressures are to be statistically processed to capture high frequency sloshing impact pressures. In this respect, The peak over threshold method can be used. The threshold to find the maxima is to be determined above the noise level in the pressure signal (Figure 5.3).

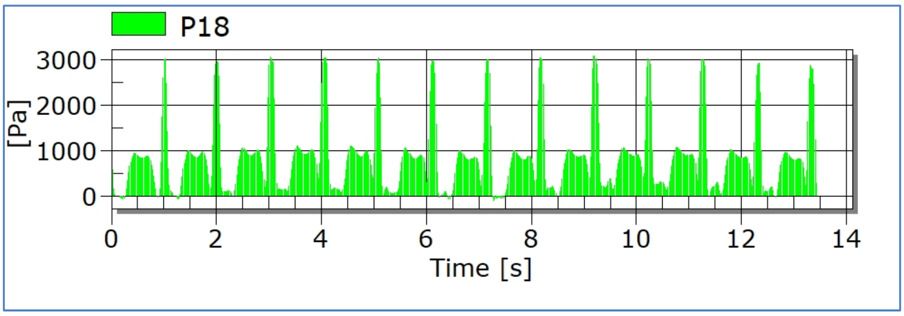

Figure 5.3. Sample of Pressure Peaks

Following data is generally processed and compared with respect to different test measurements;

- P_{max} : Maximal Value of the N recorded impact pressures,
- P_{10} : Mean of the 10 highest impact pressures,
- $P_{N/10}$: Mean of the N/10 highest impact pressures,
- $P_{N/3}$: Mean of the N/3 highest impact pressures.

The statistical distribution function (e.g. three-parameter Weibull function) to represent exceedance probability of sloshing impact pressure is to be statistically derived from the measured data. The confidence level and the selection of the statistical distribution function is to be agreed by **TL**. Similarly, long term derivation of the impact pressure loads are to be statistically analysed with respect to operational profile of the ship and submitted to **TL** for review. ITTC Sloshing Model Tests procedure (7.5-02-07-02.7) [2.7] can be used for the short term and long term approach as a guidance.

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