Guidance for Classification and Construction

Part 1 Seagoing Ships

GUIDANCE FOR SLOSHING ASSESSMENT

Volume AB

2023 Edition

Biro Klasifikasi Indonesia

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2023 Edition

Jl. Yos Sudarso No. 38-40, Tanjung Priok
Jakarta 14320 - Indonesia
rules@bki.co.id
www.bki.co.id

The following Guidance come into force on 1st July 2023.

Foreword

This Guidance for Sloshing Assessment (Pt.1, Vol.AB) is prepared with the intent of giving details as to the treatment of the various provisions for items not specified in the Rules for Bulk Carrier and Oil Tanker (Pt.1, Vol.XVII) and Rules for Ships Carrying Liquified Gases in Bulk (Pt.1, Vol. IX).

This Guidance provide methods, procedures and model test as basis for classification which consist of five Sections namely:

- Section 1 – General
- Section 2 – Methodology for Sloshing Assessment
- Section 3 – Ship Motion Analysis
- Section 4 – Sloshing Assessment Methodology
- Section 5 – Model Tests

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Table of Contents

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Section 1 General

A. Application

1. This Guidance set out assessment procedure for the sloshing impact when tanks dimensions are outside the range as defined in Rules for Bulk Carrier an Oil Tanker (Pt.1, Vol. XVII.B) Pt. 1 Ch.4, Sec. 6.6.1.2 and Pt. 1 Ch.10, Sec. 4, 1.3.7. i.e., For tanks with:

– b_{slh} > 0,56 **B** or ;
– ℓ_{slh} > 0,13 **L** for 0,05 h_{max} ≤ filling level ≤ 0,95 h_{max}

See B.1, for **L**, **B**, b_{slh}, ℓ_{slh}

2. This Guidance is to be used in conjunction with other requirements defined in Rules for Bulk Carrier an Oil Tanker (Pt. 1. Vol.XVII).

3. This Guidance may be applied for the calculation of design sloshing loads of cargo tanks for Liquefied Gas Carrier, see Rules for Ships Carrying Liquefied Gases in Bulk (Pt.1, Vol. IX).

4. When the methodology of sloshing loads assessment used by the designer differ from these Guidance, it should be consulted with BKI from beginning of the design phase for the acceptance.

B. Symbols and Abbreviations

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

L = Length of ship between perpendicular [m]

B = Breadth of ship [m]

b_{slh} = maximum effective sloshing breadth [m]

ℓ_{slh} = maximum effective sloshing length [m]

h_{max} = Maximum tank depth [m]

H_s = Significant wave height [m]

V_{max} = Maximum service speed [knot]

V_s = Service speed [knot]

CFD = Computational Fluid Dynamics

LNG = Liquefied Natural Gas

RAO = Response Amplitude Operators

C. Documents to be Submitted

1. To ensure conformity with these Guidance, the following drawings and documents are to be submitted in form of soft copy (electronic):

- 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. Additional documents and drawings may be required, if deemed necessary.

Section 2 Methodology for Sloshing Assessment

A. Introduction

1. General

This Guidance is applied for the assessment of sloshing load of double hull oil tankers with large tanks. In the design practice, violent sloshing loads mostly happened in liquefied gas carriers which have to allow partial filling level in their tanks.

In general, the arrangement of the liquefied gas carrier's cargo tanks are four tanks. In can be assume that the tank length is more than 17% of ship length between perpendiculars (> 0,17 **L**) and the breadth of tanks is extended across the port and starboard inner hull structures (> 0,85 **B**). The design of tanks commonly is membrane type in prismatic shape with top and lower chamfers.

Therefore, this Guidance provide detail explanation regarding assessment of sloshing load on samples of liquefied gas carriers.

2. Sloshing Phenomenon

Sloshing is defined as a non-linear behaviour of the liquid inside tanks that are subjected to the external forced due to ship motions on the sea. The partially liquid filled tank that induced violent sloshing due to many parameters.

The rising sloshing wave hits the tank walls is affected by ship motions, tanks geometry, filling levels, fluid density inside the tanks. The accuracy of ship motion analysis is the fundamental parameter in studying sloshing phenomenon. This conditions may become impulsive violent sloshing when the frequency of the ship motion is close to natural frequency of the tank.

In other analysis, impact pressure are strongly influenced by local phenomena such as raised edges of thanks, ratio of gas/liquid mixture or surface tension. This local phenomena influence on peak pressure over time history. Which describe variability and non-uniformly over the tanks boundaries. Therefore, analysing the sloshing phenomenon and predicting the occurrence of impact load are significantly important for the design of the tank and the safe operation since the risks involved with the structural failure of the containment structures and loss of ship stability.

There are two common techniques for studying the liquid sloshing phenomena i.e. experimental research and analytical approaches. Experimental is always a reliable and useful tool comparing to analytical approaches which have a lot of limitation. But experiments requires high time consuming and very costly to conduct. In recent years, the computational fluid dynamics (CFD) techniques which governed by Navier-Stokes (N-S) equations have become increasingly popular, due to the decreasing of computational cost by rapid development of computer technology.

B. Guide for Assessment

To assess design sloshing load is by conducting of sloshing analysis considering ship motion, filling level for given fluid density inside tanks. Scaled model test which is used for sloshing analysis, shall be supported by CFD (Computational Fluid Dynamic) analysis in order to solve for complex problem. The general guide for sloshing load assessment is provide in Fig. 2.1.

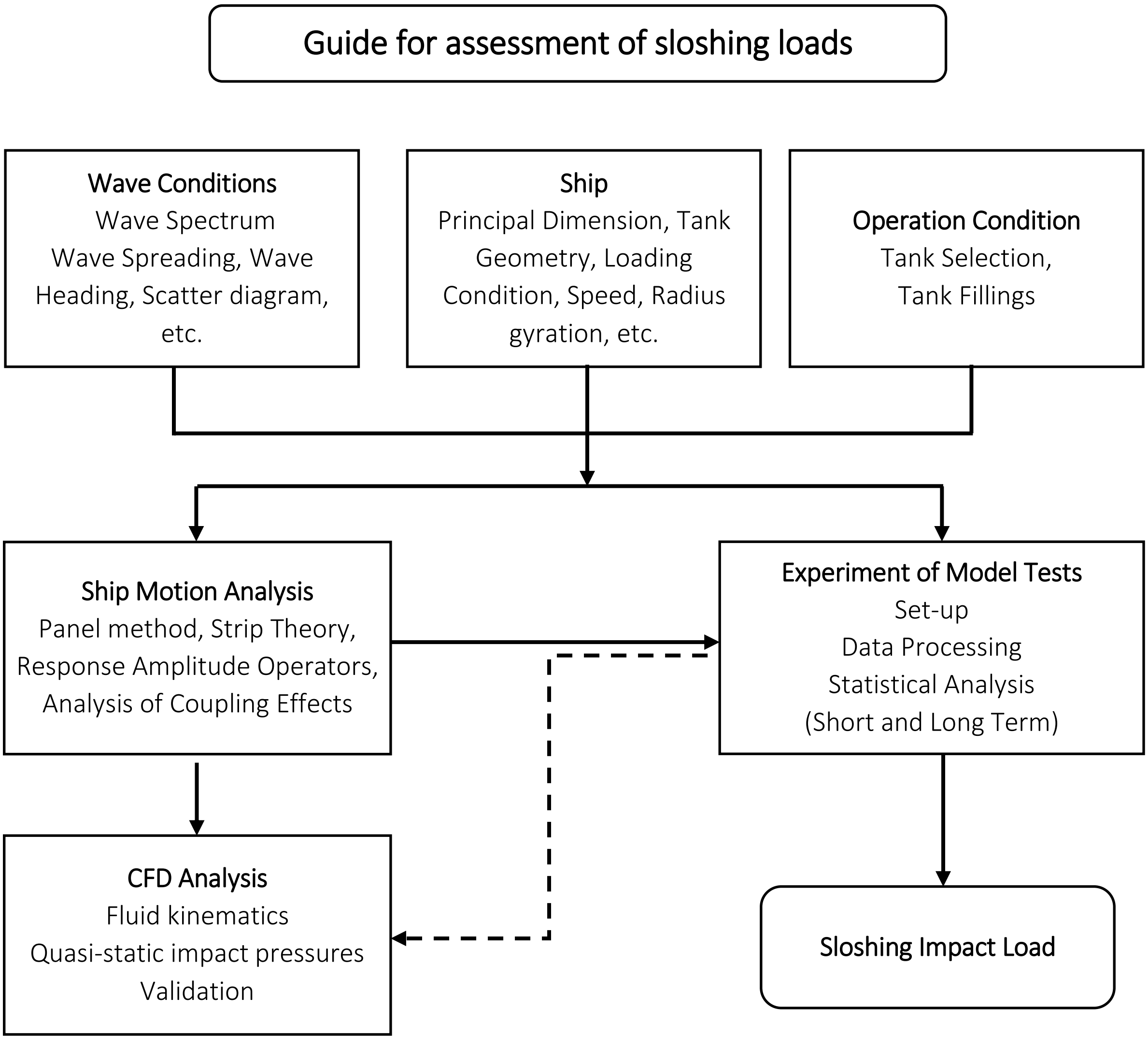


Fig. 2.1 Guide for Sloshing Assessment

In Section 3, ship motion analysis mentioned in the assessment guide will be detailed with selection of tanks and test cases, tank filling levels, ship's speed and loading conditions, and wave conditions. In Section 4, the numerical simulation by the CFD analysis will be presented. In Section 5, recommended experiment of model test set-up, data-processing and post-processing of the results will be given.

Section 3 Ship Motion Analysis

A. General

1. Aim and Purpose

The objective of Ship motion analysis is aimed at determining wave induced loads and ships motion responses under a prescribed sea state. The Calculated ship motions determined by such analysis are used as sloshing excitation for CFD calculations and sloshing model tests.

General procedure of ship motion analysis includes preparation of input data and hydrodynamic computation.

2. Basic Information

This Section explains the basic information and required inputs for ship motion analysis which will be used throughout these Guidance.

2.1 Tank Design

The tank design for the sloshing analysis is an important initial step and an input for all analysis performed in this Guidance. 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.

2.2 Ship Data

2.2.1 Hull Geometry

In order to work on motion analysis, The model preparation should be provided with following data:

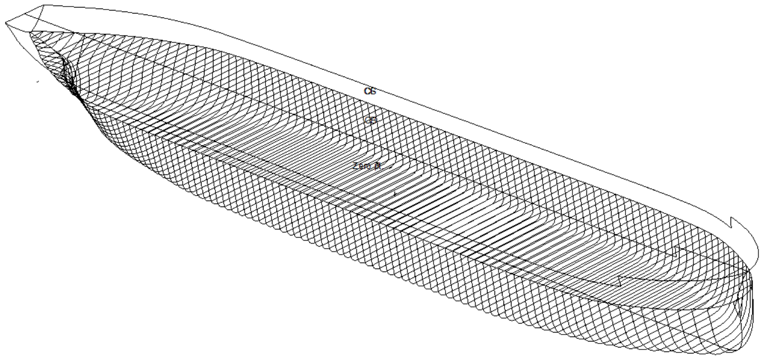
- Principal dimension of the ship and 3D hull geometry,
- Ship’s centre of gravity, draft and displacement in accordance with loading condition
- Radius gyration, Particular attention shall be paid on the calculation of the roll radius of gyration. Indeed, this roll radius of gyration will directly impact roll natural period of the ship which is an important parameter of the sloshing flow

The hydrodynamic computation is to be based on 2 options as follows:

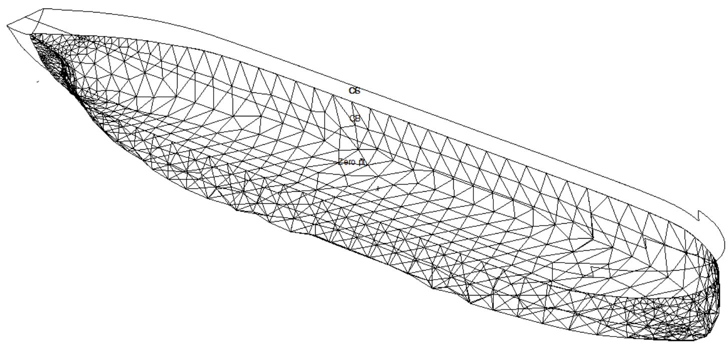
1) 3D potential theory,
   - performed by means of 3D-panel diffraction/radiation potential theory within the frequency domain software. This software has to be fully validated through the comparisons with semi-analytical studies, numerical results from recognized numerical tools and experimental results.
   - the panel representation of the hull is usually to be provided (usually about 2000 quadrilateral/triangular panels).

2) 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 (Fig. 3.1).



(a) 2D Strip Theory



(b) 3D Panel Diffraction/ radiation

Fig. 3.1 Typical hull form representations for 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.

1) For lower filling levels (< 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
2) For higher filling ratios (> 70 % H), full load condition is generally to be studied.
   - filling 70%H in all cargo tanks
   - filling 80%H in all cargo tanks
   - filling 90%H in all cargo tanks
   - filling 95%H in all cargo tanks
   - full load condition, representing the case with the worst hydrostatic properties from Loading Manual.

3) For partial filling, the coupling of ship and tank motion is to be considered for the selection of the loading condition. Following filling levels are to be evaluated 15%H, 20%H, 25%H, 30%H, 40%H, 50%H, 60%H).

2.2.3 Speed

Operating speed should be used as for input for motion analysis. The speed of the vessel has an important effect on the sloshing loads. The ship speeds need to be determined by considering the wave heading and wave height. Relative wave heading globally used in sloshing analysis are 0° – 180°. The 180° wave heading indicates head sea conditions. In general, critical heading angles for sloshing impact change with the filling height.

Practically, ship speeds need should be decreased when the ship experiences harsh waves. 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 $0° < \theta < 45°$	Quartering Seas $45° \leq \theta < 60°$	Beam Seas $60° \leq \theta < 120°$	Bow Seas $120° \leq \theta < 135°$	Head Seas $45° \leq \theta < 60°$
$H_S < 5$ m	V_{max}				
5 m $< H_S <$ 9 m	$V_{max}/2$	5 knots			$V_{max}/2$
$H_S > 9$ 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 worldwide service conditions, Standard Wave Data 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 modelled 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:

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

where,

H_s = Significant wave height [m]

A = $0{,}0081\ g^2$

B = $0{,}0032\ g^2 / H_S^2$

g = gravitational acceleration [m/s^2]

Table 3.2 Standard Wave Data for North Atlantic

T_Z (s)	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
H_S (m)																	
0.5	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	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	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	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	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	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	0.2	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	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	0.7	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	0.2	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	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	0.3	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	0.1	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	0.3	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	0.1	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	0.1	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	0.1	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	1
Sum	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

$$= 2\pi\sqrt{\frac{m_o}{m_2}} \qquad [m]$$

The assumption of short crested seas with an approved cosine 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.

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

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^o steps for wave heading are recommended from 0 – 180^o.

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/s to 1,2 rad/s in maximum increment of 0,05 rad/s. A minimum wave heading step of 15° is required. The predicted response amplitude operators (RAO) 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.

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 2.3

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

The objectives of the spectral analysis are to determine:

- the spectral moments for the 6 degrees of freedom (DOF) 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.

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

$$R(\omega_e,\beta)=\left|\eta(\omega_e,\beta)\right|^2\cdot S(\omega_e,\beta)$$

where:

$S(\omega,\beta)$ = wave spectrum

$\left|\eta(\omega,\beta)\right|$ = amplitude of the RAO

ω_e = frequency encountering [rad/s]

The moments of the response spectrum are defined as:

$$m_{\eta,n}=\int_0^{2\pi}\int_0^{\infty}\omega^n\cdot R(\omega_e,\beta)\,d\omega d\beta\text{, n = 0, 1, 2, 3, …}$$

where:

n = 0 variance (standard deviation squared),

n = 1 the first moment,

n = 2 the moment of inertia of the spectra.

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 Sloshing Assessment Methodology

A. General

1. 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

It should be recognized that the evaluation of fluid impact pressures by 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 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 experiment of model tests and for the comparative analysis with reference vessels.

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 3 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 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 3.					

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 Fig. 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.

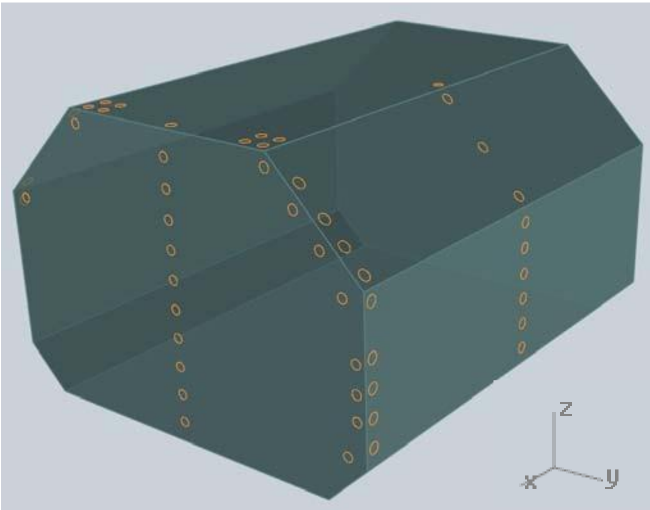


Fig. 4.1 Tank model, pressure sensor locations and coordinate system

Finite-volume discretisation techniques can be employed to solve the RANS (Reynold Averaged Navier-Stokes) 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. 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. 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 study should be refer to ITTC 7.5-03-01-01 "Uncertainty Analysis in CFD, Verification and Validation Methodology and Procedures" with at least 3 different mesh systems. 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 Fig. 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 Fig. 4.4. The measured and calculated pressure signals at various sensor locations are also comparatively presented in Fig. 4.5.

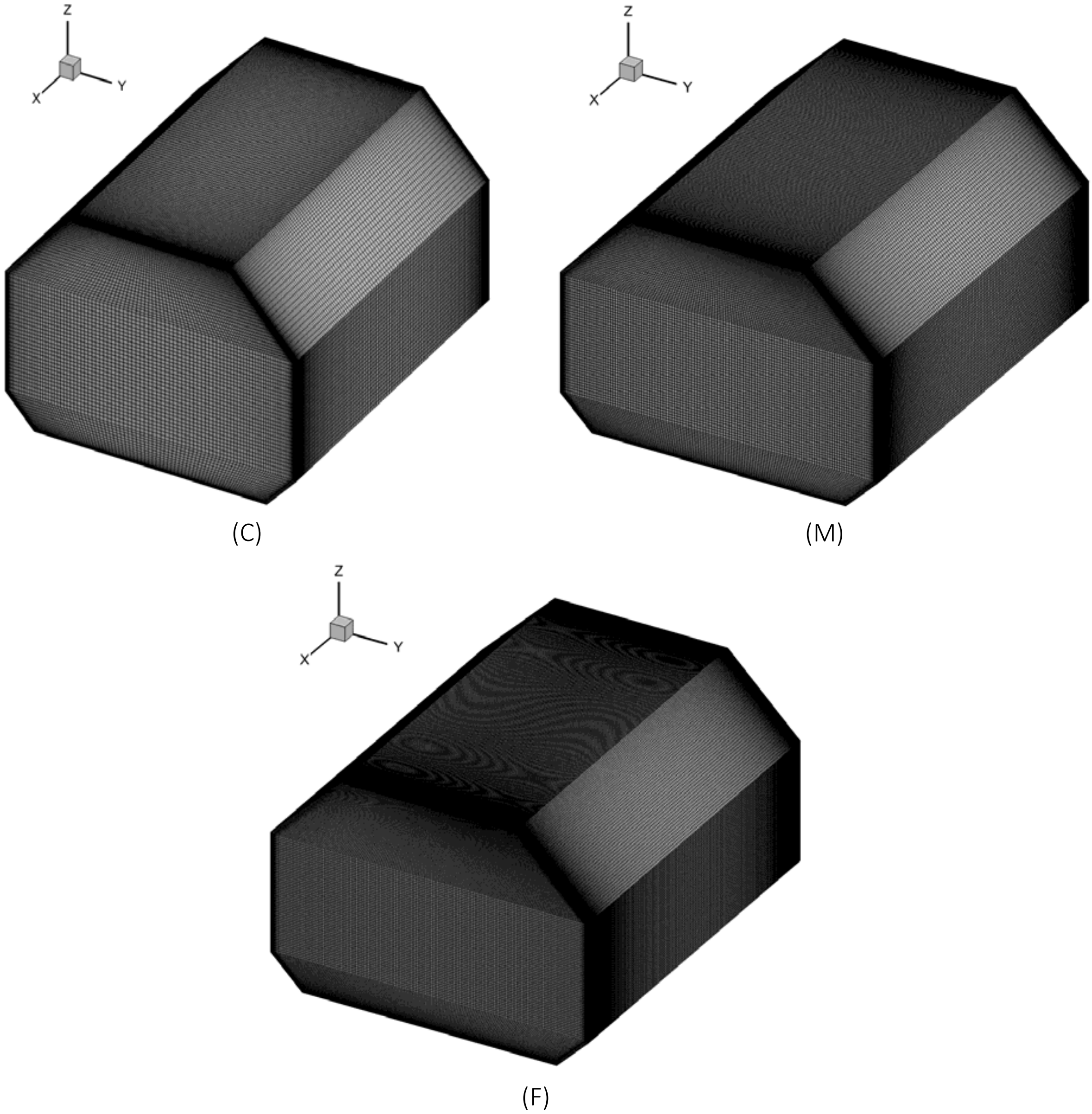


Fig. 4.2 A view of the mesh structures: Coarse (C), Medium (M), Fine (F)

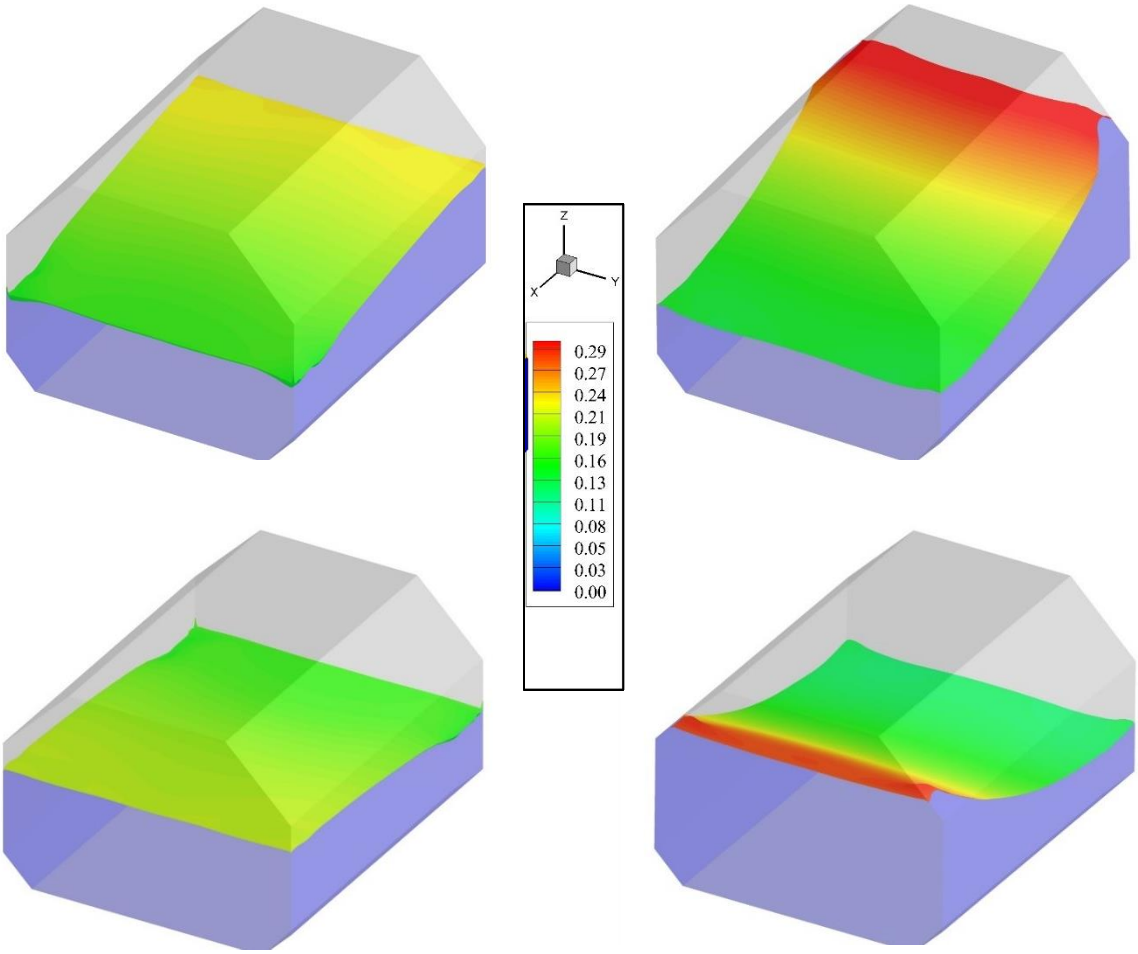


Fig. 4.4 Free surface deformations at different sloshing phases (t = T/4, t = T/2, t = 3T/4, t = T, in meters)

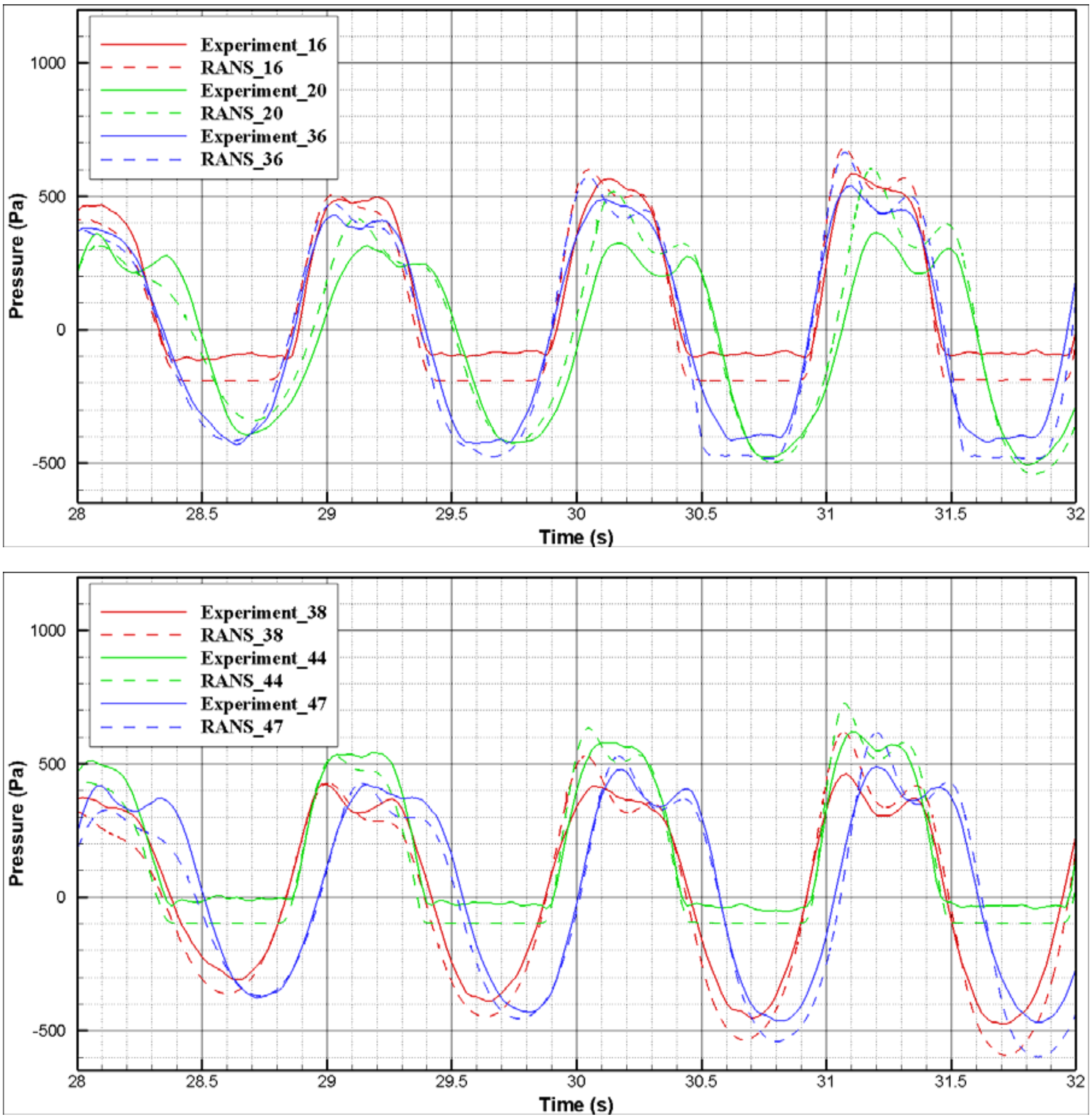


Fig. 4.5 Measured and computed pressure signals at the sensors 16, 20, 36, 38, 44 and 47

Section 5 Model Tests

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 BKI. 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 (Fig. 5.1).

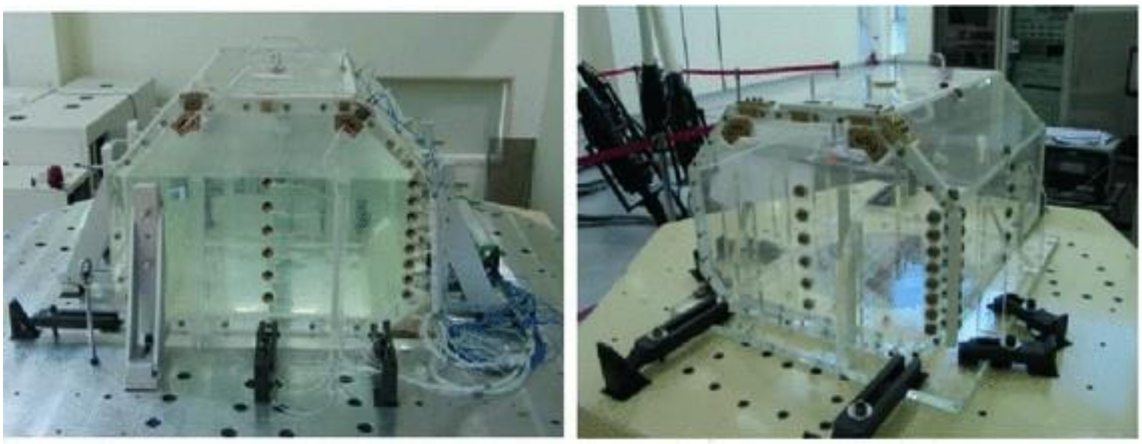


Fig. 5.1 Sample Tank Model

C. Sensors

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 Fig.5.1 and 5.2.

Drop test experiment can be conducted by 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.

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 1 m^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 sensors arrangement is to be placed on hot spot /critical point which is similar position in CFD simulation. Each hot spot is defined by a zone composed of several cells, although is not mandatory, if a study wants to capture a very localized sloshing impact, it recommended to install at least nine of the same size within an area of 1.5 m x 1.5 m at full scale, see D for sensor combination. Position 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.

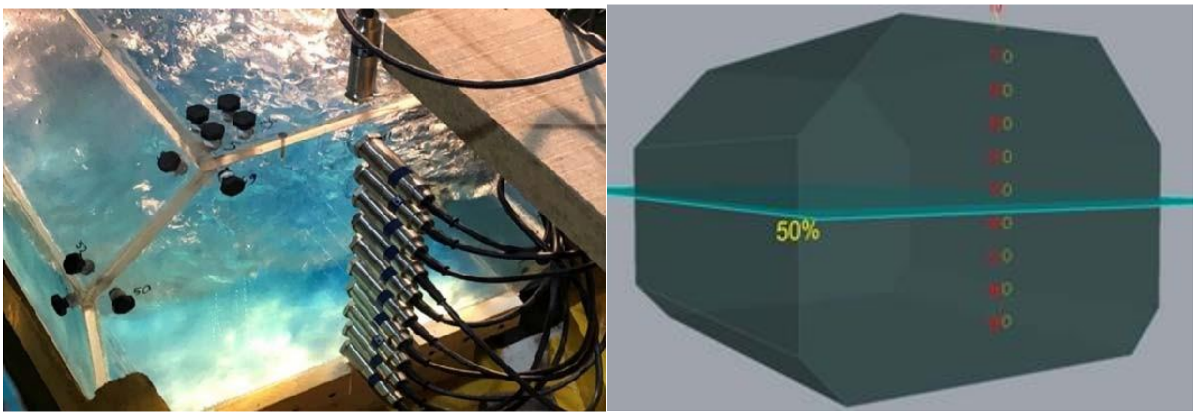


Fig. 5.2. Sample Pressure Sensor Distribution

D. Model Tests

The test matrix is to be defined to allow derivation of long-term distributions sufficiently. This may require large number of tests 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.

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 due to chamfer of model tank test, 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 2.2.2)
- 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 all sensors combinations in the impact area, as follows:

- 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.

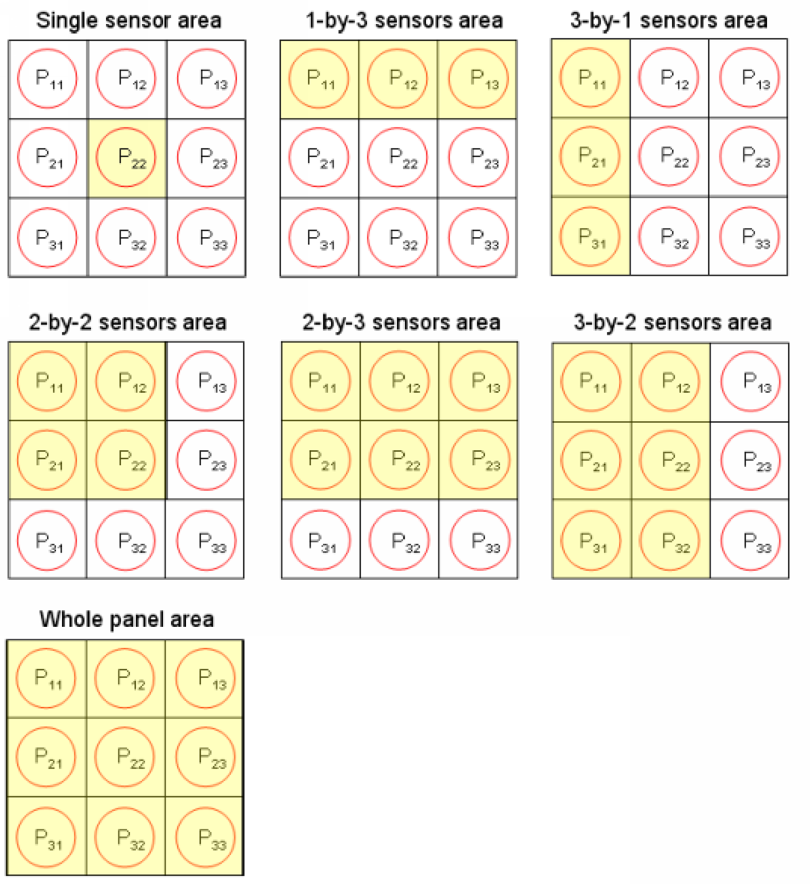


Figure 5.3. Sensors arrangement for load area processing

Dynamic characteristics 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. Froude scaling is a commonly employed scaling law in a sloshing model test. A model test is conducted based on the assumption that a test using Froude scaled tank motion can be reproduce sloshing impacts representative of real-scale condition. Therefore, the time history of tank motion can be scaled down using Froude scaling (Faltinsen et al., 1974; Olsen and Hysing, 1974). The relationship of the characteristic time between the prototype and model is expressed as follows:

$$t_p = t_m \sqrt{\frac{L_p}{L_m}}$$

Where;

t_p ; t_m = Characteristic time of prototype and model, respectively

L_p ; L_m = Characteristic Length of prototype and model, respectively

In this case, the sloshing impact load will generally be determined based on a comparative assessment with a reference design with proven service history.

E. Statistical Analysis

1 Statistical post-processing

1.1 Statistical fitting distributions

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 (Fig. 5.4).

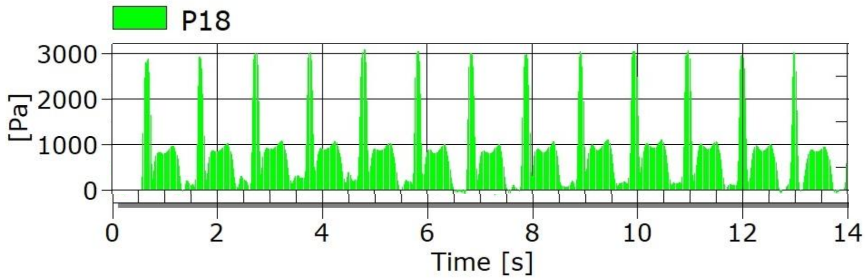


Fig. 5.4. Sample of Pressure Peaks

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.

Pressure peaks (obtained by the peak over threshold method) corresponding to each navigation condition and each loaded area 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 BKI.

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 BKI.

The present Guidance Note recommends the Generalized Pareto distribution as fitting statistical distribution unless statistical tests of goodness of fits show the contrary.

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.

1.3 Example

The above statistical post-processing is here illustrated on Fig.5.5 and Fig.5.6 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.5.7, 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 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.

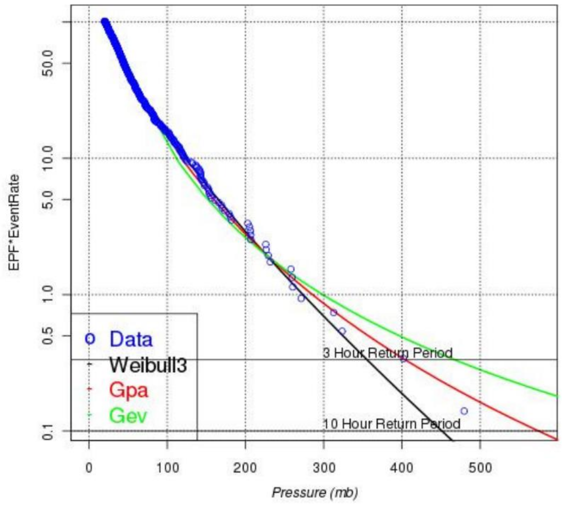


Fig. 5.5 Results of the 3 fitting distributions for one test of five hour duration

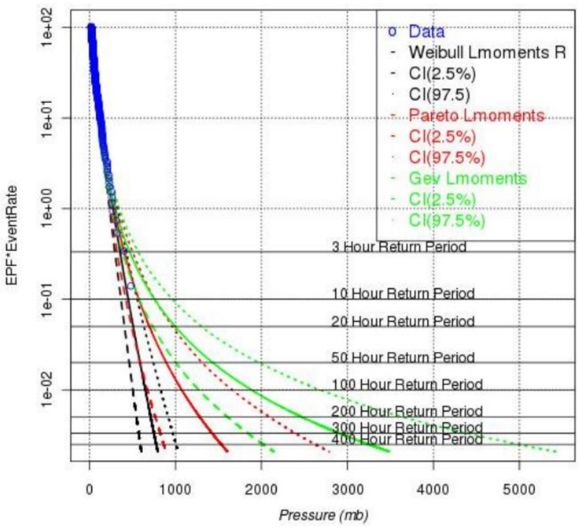


Fig. 5.6 Sample fittings by a Gpa, 3-parameter Weibull and Gev distributions, confidence intervals and return periods.

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 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 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.

3. Long Term Approach

Both observations of the few sloshing events which occurred at sea (Gervaise E., De Seze P-E. & Maillard S. (2009)) and sloshing model tests (pressures do not repeat themselves even under same drive motions). Clearly indicate variability of sloshing pressures. This stochastic behaviour 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 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.

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, 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 BKI.

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):

$$Q_{LT}(p) = 1 - \sum_{1}^{N_{ST}} \alpha_i (1 - Q_{ST_i}(P))^{3\cdot ER(i)}$$

Where;

$Q_{LT(p)}$	: 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)

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.

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

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

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).

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.5.7.

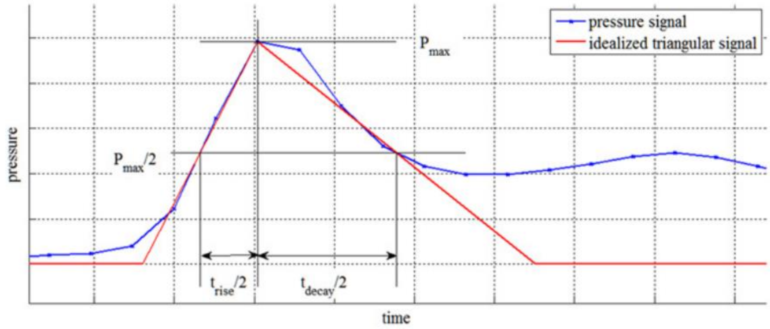


Fig. 5.7 rise and decay times definition

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 BKI.

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 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.5.8. 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.5.9. This assessment could be summarized by the following formula:

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

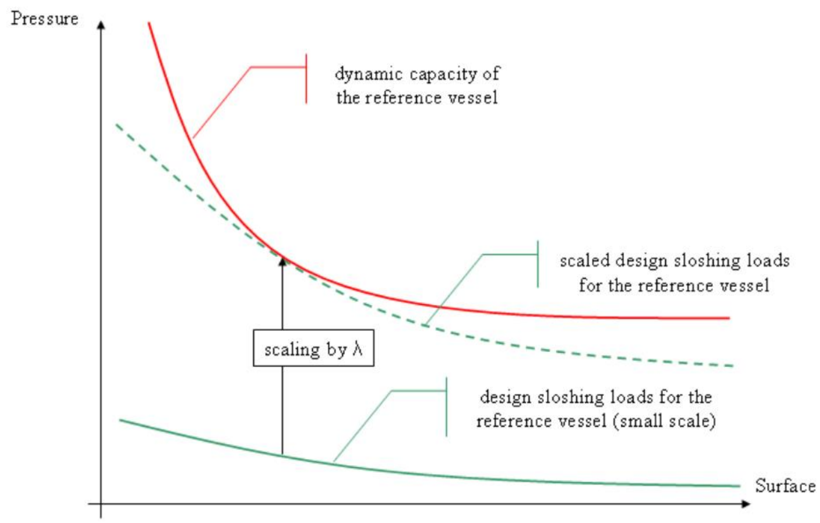


Fig. 5.8 Comparative strength assessment – step 1

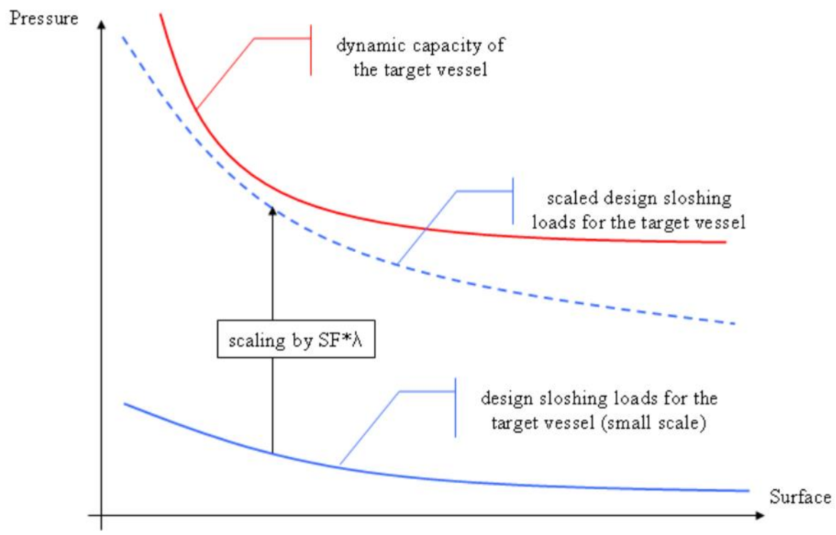


Fig. 5.9 Comparative strength assessment – step 1

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.