



GUIDANCE NOTES ON

SLOSHING AND STRUCTURAL ANALYSIS OF LNG PUMP TOWER

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ABS Plaza
16855 Northchase Drive
Houston, TX 77060 USA**

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Foreword

As the demand for Liquefied Natural Gas (LNG) grows worldwide, the size of LNG carriers increase and new tank designs emerge. The LNG industry wishes to apply more advanced and technically sound approaches for the structural assessment of the pump tower to ensure that the offered designs meet the requirements.

This document provides guidance for applying direct calculation procedures for the structural assessment of the pump tower structure. The procedures include ship motion calculation, determination of wave conditions for sloshing simulation, requirements for sloshing analysis, calculation of loads on pump tower structure, finite element analysis procedure and acceptance criteria for the strength assessment. This approach takes advantage of the principles and the experiences gained from the application of the ABS Dynamic Load Approach (DLA), advances in numerical simulation of the sloshing, and experiences from the structural analysis and evaluation of tubular structures.

In addition to the strength assessment of pump tower structure, the methodology for fatigue and vibration analysis of pump tower structure is also addressed in this document. The requirements for the strength of hull structure of LNG carriers are addressed in [Part 5C, Chapter 12 of the ABS Rules for Building and Classing Steel Vessels](#). ABS also provides *Guidance Notes on Strength Assessment of Membrane-Type LNG Containment Systems under Sloshing Loads*.

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SECTION 1 Introduction

1 Background

The design and construction of the hull, superstructure and deckhouses of an ocean-going vessel are to be based on all applicable requirements of the *ABS Rules for Building and Classing Steel Vessels (Steel Vessel Rules)*. The design criteria for an LNG carrier are located in the *Steel Vessel Rules*, Part 5C, Chapter 8. Alternative hull strength requirements in compliance with the SafeHull-based criteria are provided in [Part 5C, Chapter 12 of the ABS Rules for Building and Classing Steel Vessels](#).

Inside the LNG tank, there are two major structural systems other than the hull: LNG containment system and pump tower structure. These Guidance Notes supplement the *Steel Vessel Rules* by providing a sloshing and structural analysis procedure for the structural assessment of the pump tower. The structural assessment of the LNG containment system is addressed in the *ABS Guidance Notes on Strength Assessment of Membrane-Type Containment System under Sloshing Load for LNG Carriers*.

The pump tower system consists of pipes and pumps to load and discharge the liquid cargo and tubular members to support the structure. The pump tower is located close to the aft bulkhead, hanging over the liquid dome and connected to base support at the tank bottom, as shown in Section 1, Figure 1. The structural integrity of these systems is critical for the safe operation of the LNG carrier.

Approval of the structural design of the pump tower systems has typically been made based on the analysis and assessment provided by the manufacturers of the systems. This is a practical and well-founded practice for the review of similar designs when the previous designs have shown good service experience. As the LNG market grows, the size of LNG carriers is increasing and the operational condition is diversifying. New cargo tank designs are also emerging. The LNG industry demands a more advanced and technically sound approach for the structural assessment of the pump tower to ensure that the offered designs meet the requirements.

This document provides guidance for applying a direct calculation procedure for the structural assessment of the pump tower structure. This approach takes advantage of the basic principles and the experiences gained from the application of the ABS Dynamic Load Approach (DLA), advances in numerical simulation of the sloshing, and experiences from the structural analysis and evaluation of tubular structures.

3 The Concepts of Pump Tower Analysis Procedure

The analysis procedure provided in these Guidance Notes is a first-principle-based, direct calculation approach to identify the critical sloshing load on the pump tower during its design life and to evaluate the structural integrity of the pump tower under that load. The procedure adopts an advanced but most practical analysis method. In particular, linear seakeeping analysis, two-dimensional sloshing simulation and FE modeling/analysis of the pump tower structure by beam and plate elements are utilized.

The analysis procedure includes

- Determination of long-term extreme ship motions arising from design environmental condition
- Determination of wave conditions that may produce a large sloshing motion
- Time domain simulation of the sloshing motion of liquid cargo
- Calculation of sloshing and accompanying loads on the pump tower structure
- Structural analysis of the pump tower, using the finite element method
- Strength assessment of the pump tower structures in accordance with acceptance criteria

5 Overview of Sloshing Analysis and Structural Assessment of Pump Tower

5.1 Seakeeping Analysis of the Vessel

Section 1, Figure 2 shows the flowchart of the pump tower analysis procedure that is covered in these Guidance Notes. The procedure starts with the seakeeping analysis of the vessel, which is described in Section 2. The main objective of the seakeeping analysis is to calculate the motion of the vessel and LNG tank for a given operating and environmental condition, to be used as motion input for the sloshing analysis.

Response amplitude operators (RAOs) of ship and tank motions are calculated by linear frequency-domain ship motion analysis, from the hull form and loading conditions provided by the ship designer. Long-term extreme responses of ship and tank motion for the design environmental condition are obtained by spectral analysis.

5.3 Selection of Critical Sloshing Wave Conditions

The objective of the procedure described in Section 3 is to determine a set of regular wave conditions (wave period, heading and amplitude), called the *Critical Sloshing Wave condition* (CSWC), that are likely to produce a large sloshing motion in the cargo tank. Firstly, the *Critical Sloshing Wave Domain* (CSWD), which is a set of wave conditions (wave period and heading) that may produce a large sloshing motion, is defined based on tank motion response calculated from the seakeeping analysis and proximity of tank motion period to the sloshing natural period. Among the tank motion parameters, the local values of longitudinal and transverse acceleration at the tank center are used to determine the wave conditions in CSWD. Then, for each CSWD wave condition, equivalent regular wave amplitude is determined from the long-term responses of ship and tank motion and their corresponding RAOs. CSWCs are completely defined by determination of equivalent wave amplitude for each CSWD. Combining the selected wave conditions and tank motion RAO, the motion input for the sloshing analysis is determined.

5.5 Sloshing Analysis

For selected CSWCs, sloshing simulations are performed. Liquid motion inside the tank due to the tank motion is to be simulated in the time domain by a qualified Computational Fluid Dynamics (CFD) tool. The velocity and acceleration profile at the pump tower location are to be utilized for the evaluation of hydrodynamic force on the pump tower. Although the liquid motion inside the LNG tank is three-dimensional, sloshing analysis in three dimensions is not practical at the moment because it necessitates huge computer time and resources. Two-dimensional sloshing simulation is adopted in the current procedure. The sloshing load on each pump tower structural member is calculated by the Morison formula at each time step of the simulation. Section 4 provides a detailed description of the sloshing analysis.

5.7 Load Cases for Structural Analysis

A total of five load cases are selected for the FE analysis of the pump tower structure after completion of the sloshing analyses for all selected CSWCs. The selection is based on the total resultant force on the pump tower, which can be obtained by the integrated force from sloshing, inertial and gravitational load. The instantaneous load profile along the pump tower at the moment of maximum total resultant force is selected as input for the FE analysis. Maximum forces in the longitudinal and transverse directions are used as the selection criteria. Also considered is the maximum total resultant force transmitted to the base support to be utilized for the structural assessment of the pump tower base support. After the instantaneous profile of the dynamic loads is determined, static load due to thermal expansion (or contraction) is added for the input load for structural analysis. Details of the load cases can be found in Section 5.

5.9 FE Analysis of Pump Tower Structure

The guidance on modeling of geometries, material properties and boundary conditions of the pump tower structures are described in Section 6. The structural members of the pump tower are to be modeled by appropriate FE models such as plate, shell or beam elements to calculate the stress response of the pump tower structure to the combined load from selected load cases. The boundary conditions at the top and bottom ends of the pump tower may require special attention. Part of the liquid dome structure at the top of the pump tower is to be included in the structural model for accurate definition of the boundary condition at the top.

5.11 Acceptance Criteria

Strength criteria for tubular member, tubular joint, liquid dome cover and base plate are provided in Section 7. The LNG industry in the past often followed the *American Petroleum Institute (API- RP-2A-WSD)* for the acceptance criteria for the strength of individual structural members and tubular joints in the pump tower. This practice is more appropriate for jacket-type structures operating offshore, which have different design criteria compared to ocean-going vessels like LNG carriers. In these Guidance Notes, alternative acceptance criteria more appropriate for LNG carriers are provided following similar approaches taken for the *ABS Guide for the Buckling and Ultimate Strength Assessment for Offshore Structures* after due consideration for ocean-going vessels.

5.13 Fatigue Analysis

Fatigue strength assessment of the pump tower is described in Appendix 3, based on the hot spot stress approach. The structural details, e.g., tubular joints in the pump tower, need to be evaluated in terms of the fatigue strength. Applicable dynamic loads are considered. Appropriate SCFs (Stress Concentration Factors) are to be applied in the stress range calculation.

5.15 Vibration Analysis

Vibration assessment of the pump tower is described in Appendix 4. The free and forced vibration of pump tower due to main engine and propeller are considered. The analysis procedure provides guidance on the selection of loading conditions, tank location and filling levels, boundary conditions and critical areas to investigate. Excessive vibration is to be avoided in order to reduce the risk of structural damage such as cracking on the liquid dome, base plate, or tubular joints of pump tower structure. The acceptance criteria for pump tower vibration are provided in terms of the vibration limits for local structures, taken from *ABS Guidance Notes on Ship Vibration* (2006).

FIGURE 1
Typical Pump Tower Installed in LNG Tank

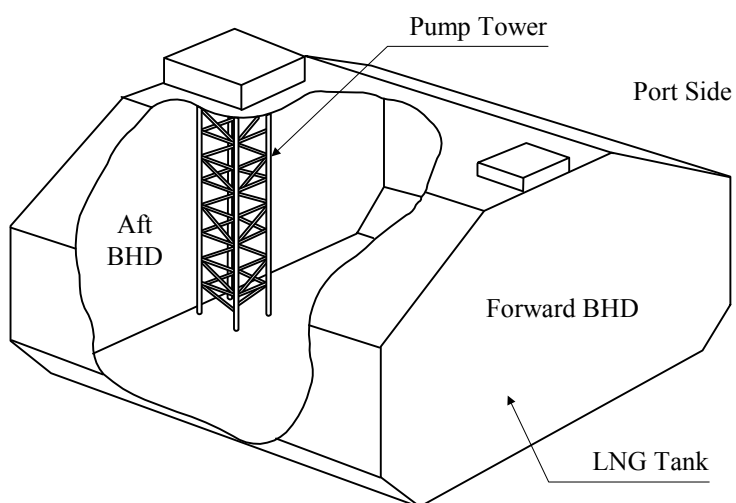
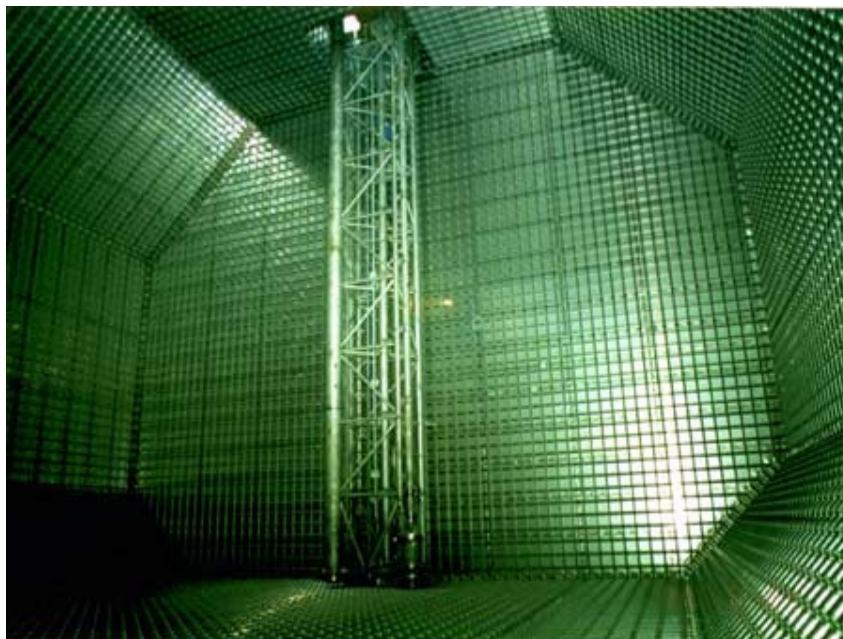
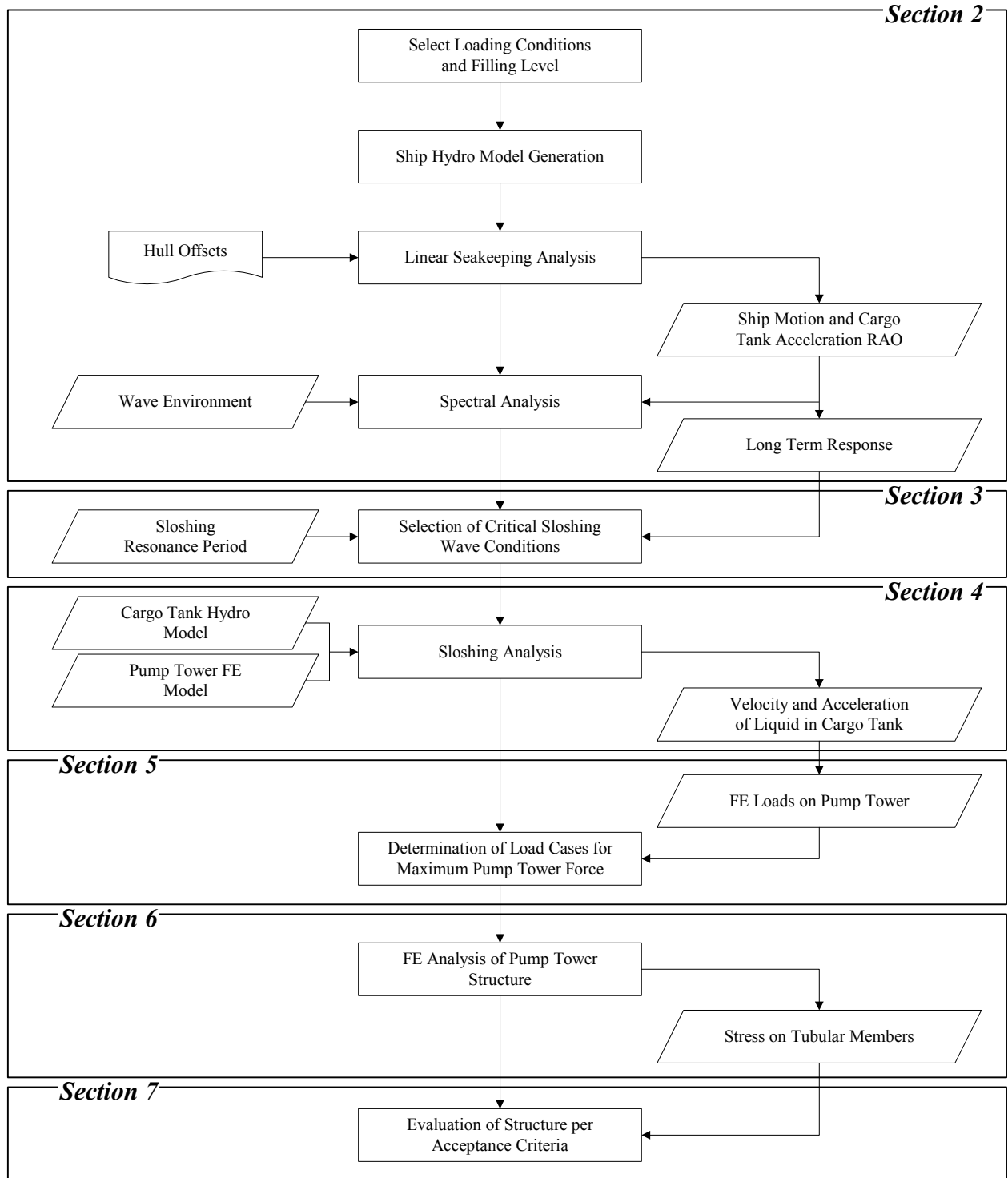


FIGURE 2
Flowchart for Sloshing Analysis and
Structural Assessment of Pump Tower



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SECTION 2 Analysis of Ship Motions

1 Overview

This Section lists the essential features concerning the calculation of ship and tank motions. It is expected that such calculations will be made using the Spectral-based approach, which relies on the use of *Response Amplitude Operators* (RAOs). Each RAO is to be calculated for regular waves of unit amplitude for ranges of wave frequencies and wave headings that will be specified below. This Section also specifies the expected outcome of analysis to establish the *Long-Term Response* (LTR) of ship and tank motions. The RAO and LTR will be used to determine the wave condition and tank motion for the sloshing analysis.

3 Environmental Condition

3.1 Wave Scatter Diagram

For unrestricted service, a 25-year return period using wave statistics of the North Atlantic is ordinarily specified to establish design values for controlling environmentally-induced effects. For an LNG carrier, environmentally-induced loads are dominated by waves, which are characterized by significant heights, spectral shapes and associated wave periods.

Unless special design consideration is granted, an LNG carrier is assumed to operate for unrestricted services. The standard wave data for design reviews for vessels of unrestricted services is given as the wave scatter diagram provided by the IACS Recommendation No.34 (Nov. 2001), see Section 2, Table 1. The wave scatter diagram provides the probability or number of occurrences of sea states in a specified ocean area. The number in each cell gives the probability of the sea states for the given zero-crossing period, T_z , and significant wave height, H_s . The probability of each sea state is given in terms of the number of occurrences among 100,000 occasions.

3.3 Wave Spectrum

The two-parameter Bretschneider spectrum is used to model open sea wave conditions in the seakeeping analysis and the “cosine squared” spreading is applied to model short crest waves. The wave spectrum is given by:

$$S(\omega, \theta) = \frac{2}{\pi} \cos^2 \theta \cdot \frac{1.25 \omega_p^4 H_s^2 e^{-1.25(\omega_p/\omega)^4}}{4\omega^5}$$

where

S	=	wave energy density, in $\text{m}^2\text{-sec}$
ω	=	angular frequency of wave component, in rad/sec
θ	=	wave heading, in rad
ω_p	=	peak frequency ($= 2\pi/T_p$) in rad/sec
H_s	=	significant wave height, in m

TABLE 1
Standard Wave Data Recommended by IACS

	Tz (sec)																	
Hs (m)	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	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	0.2	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	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	

5 Ship Design Considerations

5.1 Operational Condition

It is assumed that during its service life the LNG carrier operates in the design wave environment, defined by the wave scatter diagram in Section 2, Table 1, with equal probability of all wave headings. It is also to be assumed that ship maintains 75% of design speed during the voyage for all sea states under consideration.

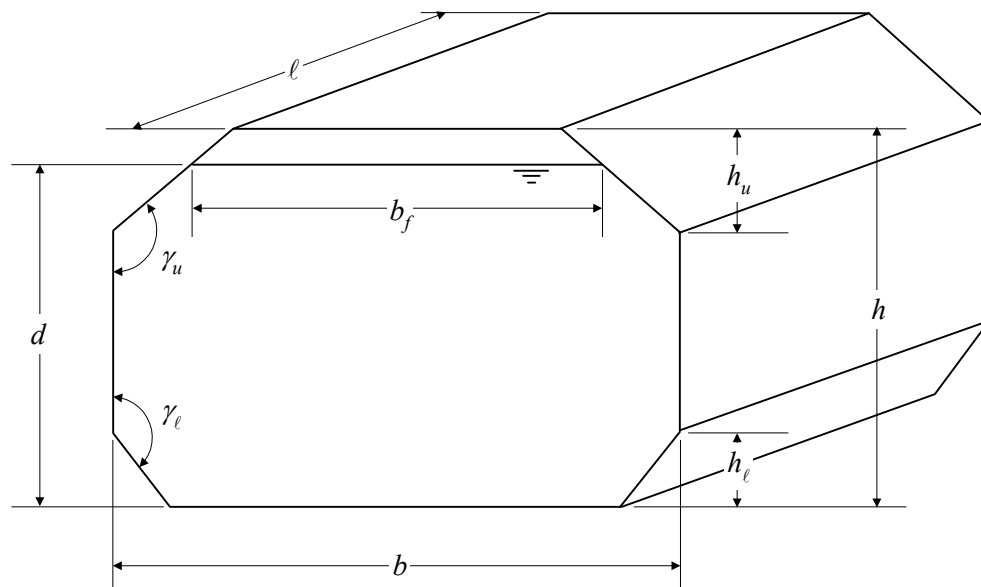
5.3 Filling Levels

Filling levels for the sloshing analysis are to be selected based on the loading manual provided by the designer. Otherwise, the standard filling levels plus selected representative partial filling levels are to be analyzed. Filling levels are usually given in terms of relative filling height to the tank height, h , (%H) or the tank length, ℓ , (%L). Section 2, Figure 1 shows a definition sketch of a typical membrane-type LNG tank. All of the dimensions are defined for the inner surface of the LNG tank. The thickness of the containment system is to be deducted when calculating tank dimensions from hull drawing.

“Standard filling level” denotes filling levels higher than 70%H and lower than 10%L for LNG carriers with capacity lower than 150,000 m³. The following filling levels are to be considered in the sloshing analysis for pump tower analysis: 10%L, 70%H, 80%H, 90%H and 95%H.

When there is no restriction on filling level, the following filling levels are to be considered in the sloshing analysis in addition to the standard filling levels: 25%H, 30%H, 40%H, 50%H and 60%H.

FIGURE 1
Definition Sketch of Membrane-Type LNG Tank



b :	tank breadth	h :	tank height
b_f :	breadth of the still water surface	d :	filling height
Filling level = d/h (%H) or d/ℓ (%L)			
h_l :	lower chamfer height	h_u :	upper chamfer height
γ_l :	lower chamfer angle	γ_u :	upper chanfer angle

5.5 Loading Conditions

The draft, metacentric height and center of gravity of the vessel, which are important parameters for seakeeping analysis, are different for each filling level. Seakeeping analysis for each filling level is to be performed with the loading conditions provided in the loading manual.

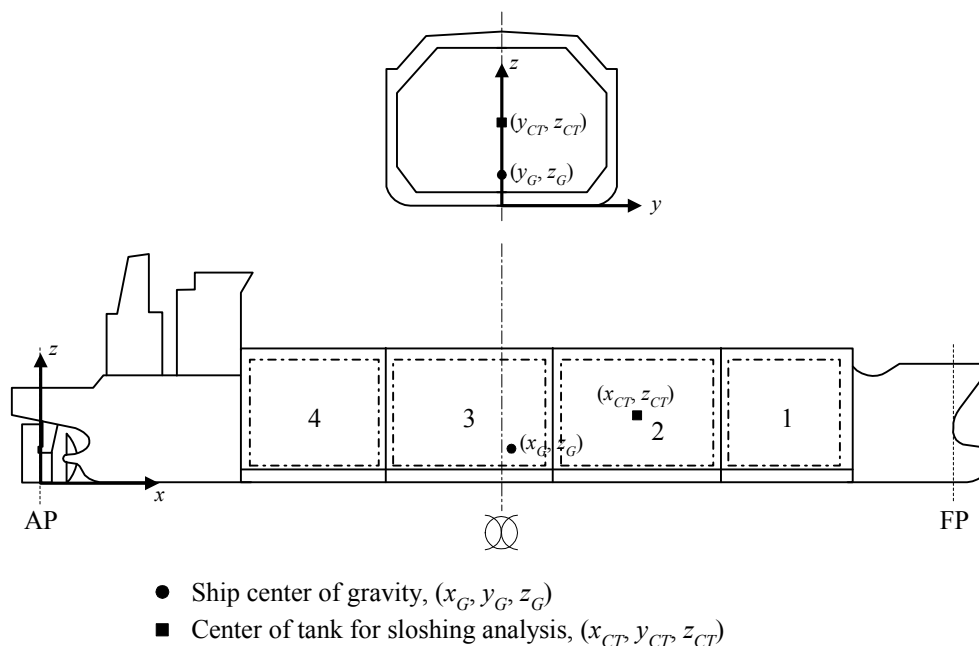
For standard filling levels, the following two representative loading conditions can be used for high and low filling levels:

- *Filling levels higher than or equal to 70%H*: Full load condition at arrival
- *Filling levels lower than or equal to 10%L*: Ballast condition at arrival

5.7 Tank Location

LNG carriers usually have 4 to 5 tanks. Section 2, Figure 2 illustrates an LNG carrier with 4 tanks. The forwardmost cargo tank (No. 1 tank) is usually smaller than the other tanks and may have a tapered shape to conform to the bow area. The other cargo tanks are usually similar in size with a uniform transverse cross-sectional shape. In most cases, the No. 2 tank is considered to have the highest sloshing motion due to its size and distance from the ship motion center. Sloshing analysis is to be carried out for the No. 2 tank.

FIGURE 2
LNG Cargo Holds and No. 2 Tank Location



7 Spectral Analysis of Motion and Wave Load

7.1 General Modeling Considerations

The hull-geometry of an LNG carrier is to be accurately modeled from the offset data provided by the designer. The location of the center of gravity, mass and mass moment of inertia for each loading condition and filling level are to be obtained from the loading manual provided by the designer.

Sometimes, radii of gyration of LNG carriers are not provided in the early design stages of the vessel. The following empirical value can be used when those data are not available:

$$r_{xx} = \begin{cases} 0.35B, & \text{for full – load condition} \\ 0.45B, & \text{for ballast condition} \end{cases}$$

$$r_{yy} = r_{zz} = 0.25L_{pp}$$

where

r_{xx} = roll radius of gyration

r_{yy} = pitch radius of gyration

r_{zz} = yaw radius of gyration

B = breadth of vessel

L_{pp} = length between perpendiculars

7.3 Diffraction-Radiation Methods and Panel Model

Computations of the wave-induced motions are to be carried out through the application of seakeeping analysis codes utilizing three-dimensional potential flow-based diffraction-radiation theory. All six degrees-of-freedom rigid-body motions of the vessel are to be accounted for. These codes, based on linear wave and motion amplitude assumptions, make use of boundary element methods with constant-source panels over the entire wetted surface of the hull on which the hydrodynamic pressures are computed.

Boundary element methods, in general, require that the wetted surface of the vessel be discretized into a large number of panels. The panel is to be fine enough to resolve the incoming and diffracted wave with reasonable accuracy. It is recommended that at least four panels be included within one wavelength.

If seakeeping analysis tools other than those provided by the Bureau are used, the results of the seakeeping analysis for the benchmark LNG vessels provided by the Bureau are to be submitted to the Bureau to ensure that the seakeeping tools are compatible with the procedures provided in these Guidance Notes.

7.5 Roll Damping Model

The roll motion of the vessel in oblique waves is greatly affected by the viscous roll damping of the hull, especially near the roll resonance. For seakeeping analysis based on the potential flow theory, a proper viscous roll damping modeling is to be introduced in the panel method. Experimental data or empirical methods for the roll damping model can be used in consultation with the Bureau for the determination of the viscous roll damping of the hull. The roll damping effects due to rudders and bilge keels is also to be considered in the seakeeping analysis. If that information is not available, 10% of critical damping may be used for the overall viscous roll damping.

7.7 Vessel Motion and Tank Acceleration Response Amplitude Operators

RAOs are to be calculated for the six degrees of freedom global vessel motion and local accelerations at the center of the tank. Only these responses need to be considered for the calculation of extreme values. The transverse and longitudinal acceleration at the tank center is defined in the moving coordinate system fixed at the tank and includes the effect of inclination and gravity:

- Longitudinal acceleration at tank center:

$$A_x = \ddot{X}_1 + (z_{CT} - z_G) \ddot{X}_5 - (y_{CT} - y_G) \ddot{X}_6 + gX_5$$

- Transverse acceleration at tank center:

$$A_y = \ddot{X}_2 - (z_{CT} - z_G) \ddot{X}_4 + (x_{CT} - x_G) \ddot{X}_6 - gX_4$$

- Vertical acceleration at tank center:

$$A_z = \ddot{X}_3 + (y_{CT} - y_G) \ddot{X}_4 - (x_{CT} - x_G) \ddot{X}_5$$

where

- $x_G, y_G, z_G =$ ship center of gravity, in m
- $x_{CT}, y_{CT}, z_{CT} =$ center of tank for sloshing analysis, in m
- $g =$ gravitational constant ($= 9.8065 \text{ m/s}^2$)
- $X_1, \ddot{X}_1 =$ surge and longitudinal acceleration at the ship C.G., in m, m/s^2 , respectively
- $X_2, \ddot{X}_2 =$ sway and lateral acceleration at the ship C.G., in m, m/s^2 , respectively
- $X_3, \ddot{X}_3 =$ heave and vertical acceleration at the ship C.G., in m, m/s^2 , respectively

$X_4, \ddot{X}_4 =$ roll and roll acceleration, in rad, rad/s², respectively

$X_5, \ddot{X}_5 =$ pitch and pitch acceleration, in rad, rad/s², respectively

$X_6, \ddot{X}_6 =$ yaw and yaw acceleration, in rad, rad/s², respectively

The locations of center of gravity of the ship and tank are shown in Section 2, Figure 1.

The RAOs are to represent the pertinent range of wave headings, θ , in increments not exceeding 15 degrees, from following seas (0 degrees) to head seas (180 degrees).

It is important that a sufficiently broad range of wave frequencies is considered. The recommended range is 0.2 radians/second (rad/s) to 1.2 rad/s, in increments of 0.05 rad/s.

In these Guidance Notes, RAOs for surge, sway, heave, roll, pitch and yaw motion will be referred to as $RAO_1, RAO_2, \dots, RAO_6$, respectively. The longitudinal, transverse and vertical RAOs will be referred to as RAO_7, RAO_8 and RAO_9 , respectively.

9 Long-Term Response for Ship Motions

Extreme-value analysis is to be performed to determine lifetime maximum values for each ship motion and acceleration, which will be used when selecting wave conditions and tank motion for the critical sloshing load. Preference is given to an extreme-value method that follows the so-called long-term approach commonly used for ship structure.

Note: A useful reference to explain concepts and terminology associated with extreme value analysis is “Wave Statistics for the Design of Ships and Ocean Structures”, by M.K. Ochi, SNAME Transactions, Vol. 86, 1978, pp. 47-76.

The relevant lifetime maximum value to be obtained from the long-term analysis is the Long-Term Response (LTR), having an exceedance probability level of 10^{-8} . This probability level is ordinarily considered to be equivalent to a return period of 25 years.

In these Guidance Notes, lifetime maximum values for surge, sway, heave, roll, pitch and yaw motion will be referred to as $LTR_1, LTR_2, \dots, LTR_6$, respectively. The longitudinal, transverse and vertical acceleration RAOs will be referred to as LTR_7, LTR_8 and LTR_9 , respectively.