ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

Sloshing Model Tests

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Sloshing Model Tests

1. PURPOSE OF PROCEDURE

This procedure outlines the recommended state-of-the-art practice of a sloshing model test for the observation of sloshing flow and impact pressure under operational and environmental conditions.

The procedure describes the requirements for the preparation of the sloshing model test such as the motion platform, model tank, pressure sensor, and possible model configurations. It also provides recommendations for data measurements, and the operational and environmental parameters that should be included in the test matrix. In addition, the procedure outlines the recommended approach for a data analysis.

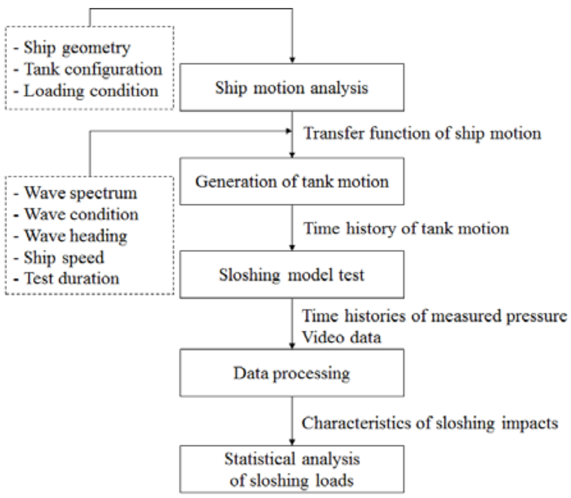

Figure 1: Flowchart of sloshing model test

2. SLOSHING MODEL TEST

The main purposes of a sloshing model test are to generate a realistic fluid flow inside the tank and estimate the extreme sloshing load on the tank wall. A general flowchart of the sloshing model test is shown in Figure 1.

2.1 Preparation of Test Matrix

2.1.1 Wave Conditions

Sloshing model tests should be carried out in waves corresponding to the sea conditions under which a vessel may be required to operate. The wave environment should be presented as a sea state based on a wave scatter diagram. A wave scatter diagram gives the joint probability of particular wave conditions represented by a significant wave height and wave zero crossing period. A scatter diagram is dependent on the characteristics of the ocean. For example, the waters of the North Atlantic are generally represented as IACS - No 34 standard wave data.

The wave environment should be selected based on the objectives of the test. It is generally recommended to cover various wave conditions for a fixed return period. In this manner, wave contours can be obtained. The particular short-term sea state can be represented by a wave spectrum. In the absence of specific wave spectrum data, the ITTC spectrum can be used for the open ocean and a JONSWAP spectrum can be used for fetch-limited seas.

2.1.2 Filling Height

The tester should specify the tank fillings while considering the tank type. In general, sloshing model tests are conducted for liquefied natural gas (LNG) carrier and LNG offshore platforms. Conventional LNG carriers with membrane-type cargo systems have filling restrictions of between 10–70% of the tank height. This is because very large sloshing impacts occur under partially filled conditions, particularly for 20–40% of the tank height. However, intermediate filling heights cannot be avoided for most LNG platforms with the exception of an LNG carrier.

2.1.3 Heading Angle and Ship Speed

The wave heading conditions and ship speed need to be determined before conducting the model tests for irregular sea conditions. Relative wave headings globally used in sloshing tests are 90-180° with 30° discretization, among which, a 180° wave heading indicates head sea conditions. In general, critical heading angles for sloshing impact change with the filling height.

Ship speeds need to be determined by considering the wave heading and wave height. The ship speed should be decreased when the ship experiences harsh waves (ABS, 2014; BV, 2013; DNV, 2014; LR, 2009). With a lack of any other information, Table 1 can be used a guideline for the ship speed applied to the test agenda.

Table 1. Example of ship speed determination for different wave heights and wave headings

Wave Height (Hs)	Wave heading (θ)	
	$\theta < 45°$, $\theta > 135°$	$45° < \theta < 135°$
Hs < 5m	Full service speed, V (knots)	
5m < Hs < 9m	0.5 V (knots)	5.0 (knots)
Hs > 9m	5.0 knots	

2.1.4 Tank Motion

A reliable ship motion program should be used to generate the ship motion in waves. If model tests have to be conducted for various wave headings including the head sea conditions, it is recommended to use a three-dimensional ship motion program. The calculation should provide a linear ship motion transfer function that can be applied to simulate irregular ship motion for particular short-term sea conditions.

In a strict sense, owing to partially filled tanks, dynamic coupling between fluid sloshing and ship motion needs to be considered during a motion calculation.

Using the provided motion transfer function and a specified wave spectrum, the time history of irregular ship motion under particular sea conditions be generated. This can be achieved through an inverse Fourier transformation of the transfer function. To avoid the periodicity of the generated irregular motion, it is recommended to apply a large number of wave components (e.g., more than 200 components and non-uniform discretization). The generated ship motion should be converted into the tank motion. Therefore, it is important that the tester be informed regarding the reference point of ship motion calculation and the relative location of the tank with respect to this reference point.

2.1.5 Test Duration

Care must be taken in selecting the duration of the data acquisition so that sufficient data are recorded for the objective of the test. Owing to a large variability of sloshing impact pressure, long duration tests are required to obtain reliable test results. For instance, if the exceedance probability distribution of sloshing pressures below the 1/N probability level is desired, the test time should be sufficiently long to acquire more than 10 x N impact samples.

2.2 Scaling Law

2.2.1 Scaling Law for Tank Motion

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 reproduce sloshing impacts representative of real-scale conditions. 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:

$$t_p = t_m \sqrt{\frac{L_p}{L_m}} \tag{1}$$

where t is the characteristic time and L is the characteristic length. The subscripts p and m denote the prototype and model, respectively.

2.2.2 Scaling Law for Measured Pressure

The pressure measured in a model-scale test should be scaled up to the real scale. In general, Froude scaling can be applied for the time history of the sloshing pressure. In Froude's law, the effects of fluid viscosity, compressibility, and condensation are ignored. However, the sloshing impact may involve other complex local phenomena such as a gas pocket between the wave and tank wall or small bubbles around the measurement area. In such a case, Froude scaling can result in overly conservative results and Euler's scaling law may be appropriate (Karimi et al., 2014). The pressure value for the prototype and model, based on two different scaling laws, can be expressed as follows:

Froude scaling $$P_p = P_m \frac{\rho_p}{\rho_m} \frac{L_p}{L_m} \tag{2}$$

Euler scaling $$P_p = P_m \frac{\rho_p c_p}{\rho_m c_m} \sqrt{\frac{L_p}{L_m}} \tag{3}$$

where P is the pressure, ρ is the liquid density, and c is the speed of sound in a fluid.

2.3 Motion Platform

2.3.1 Capability of Motion Platform

The motion platform should be able to simulate the tank motion. For an irregular motion test, in particular, six degree of freedom (6dof) tank motions should be simulated. The pre-defined time history of tank motion calculated based on a ship motion analysis is applied as input data to the motion controller. Commonly used motion platforms include a hexapod-type motion platform, which can simulate 6dof motion using six actuators (Figure 2).

Figure 2: Hexapod-type motion platforms (Seoul National University)

In terms of capability of the motion performance, the motion platform should be designed in consideration of the worst tank motions expected to be simulated. The model scale of the targeted tank is one of the key parameters for the platform design.

It is recommended to check the capacity of the motion platform, not only for 1dof motions but also for combined 6dof motions. The displacements, velocities, and accelerations of the 6dof motions should be checked carefully. Furthermore, the load capacity should be sufficiently large to excite the targeted model tank filled with liquid (Gavory, 2005).

2.3.2 Verification of Motion Performance

The motion platform should apply the specified tank motion accurately. The accuracy of the motion platform needs to be verified using an independent motion measurement system. During the accuracy measurement, the motion platform should be applied with the maximum payload. If the agreement between the input motion and the output motion is unacceptable, the motion platform should be calibrated for better performance.

2.4 Tank Model

2.4.1 Tank Model

The model tank needs to be made of transparent material allowing the sloshing flow inside the tank to be observed. Unless the hydroelasticity of the tank structure is considered, the model tank should be sufficiently stiff that the natural frequencies of the model tank do not interfere with the sloshing event. In general, the inner side surface of the tank wall is flat, with the exception of internal structures such as an invar edge or corrugation. If necessary, a simplified pump tower can be installed in the model tank.

The model tank should be able to have pressure sensors mounted at various sloshing hotspots inside the tank wall. It is preferable to mount the pressure sensors in a cluster in order to capture the local sloshing impact and view the pressure distribution. To minimize pressure noise from unwanted fluid-structure interaction, the pressure sensors are to be mounted as securely as possible using firm mounting devices. In addition, the pressure sensors are mounted flush with the inner side of the tank wall.

2.4.2 Fluids in the Tank

For practical purposes, ambient air and water can be used as two fluids filled inside the model tank. However, it should be noted that the density ratio of air and water is different from that of natural gas (NG) and liquefied natural gas (LNG). To improve the similarity of the density ratio in a sloshing model test, it is recommended to replace ambient air by a suitable ullage gas that is heavier than air (Maillard and Brosset, 2009).

A mixture of sulphur hexafluoride (SF6) and nitrogen (N2) can be used as an alternative. The proper proportion of these two constituents should be used during the test. To use a particular gas, the model tank should be designed for gas injection. It is generally known that replacing ambient air with a heavier gas decreases the magnitude of the sloshing pressure, particularly for gas-pocket type impacts because of the increase in momentum transfer between the liquid and gas during impact (Figure 3).

Even if the mixture gas is fully injected initially, dissolved air will still be present inside the water, which may change the property of the gas while the tests are being conducted. Hence, the water should be fully saturated with the gas before the test is conducted. A proper gas measuring device is needed to check whether the tank is filled with the intended gas (Ahn et al., 2012).

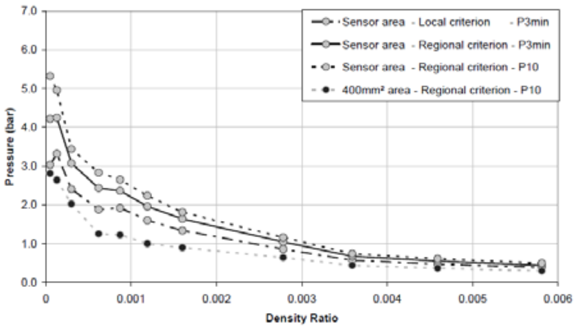

Figure 3: Pressure results vs. density ratio for several criteria of post-processing (Maillard and Brosset, 2009)

Under certain conditions, sloshing events can be very sensitive to the liquid filling height. Therefore, accurate dimensioning of the liquid filling height is important. The targeted filling height should be marked at the inside of the tank wall, rather than the outside of the wall (the refraction of light makes it difficult to measure the liquid filling height accurately). Controlling the volume of fluid to be injected can be a good way to increase the accuracy of the liquid filling height.

2.5 Data Measurement

2.5.1 Pressure Sensor for Sloshing Model Test

The requirements of a pressure sensor for use in a sloshing model test are as follows:

- The pressure sensor should be applicable under wet conditions, and preferably insensitive to temperature fluctuations (Kim et al., 2015).
- A flush-mounting type sensor is recommended such that pressure sensor does not interfere with the flow inside the tank.
- The size of the effective sensing area should be small such that the local sloshing impacts can be captured, and the pressure sensor itself should be sufficiently small to enable the sensors to be installed as a cluster.
- The pressure sensors should have strong shock resistance and the measured pressure must not be interfered with by the structure during tank excitation, sloshing impact, or other possible noise sources. In addition, motor noise from the motion platform should not be so large that it interferes with the pressure measurements.
- The measurement capacity of the pressure sensor should be sufficiently higher than the expected sloshing pressure.
- The response of the pressure sensor should be sufficiently high to allow the sloshing impact to be captured (Repalle et al., 2010). The response of the pressure sensor is closely related to the sensor's natural frequency.

2.5.2 Calibration of Pressure Sensor

Pressure transducers should be calibrated through an impact test. As an impact test, a wedge drop test with a small dead rise angle is recommended. During the test, pressure sensors should be flush mounted to the wedge surface, which will be dropped down into the water. The magnitude and shape of the pressure impulse can be compared with existing experimental and theoretical studies. (Wagner, 1932; Dobrovl'skaya, 1969; Zhao, 1997; Chuang et al., 1966; Kim et al, 2016)

2.5.3 Arrangement of Pressure Sensors

The arrangement of the pressure sensors should be determined based on the objectives of the test and the test conditions. Typical hotspots of sloshing impact for a membrane-type LNG cargo tank are shown in Figure 4. The hotspots are the corners and edges of the tank roof and upper-chamfers under high filling conditions. Under low filling conditions, the hotspots are the side walls of the tank near the filling height, and the intersections between the side walls and upper-chamfers. The sensors need to be positioned close to the edges.

Although is not mandatory, if a study wants to capture a very localized sloshing impact, it is recommended to install at least nine pressure sensors within an area of 1.5 m x 1.5 m at full scale.

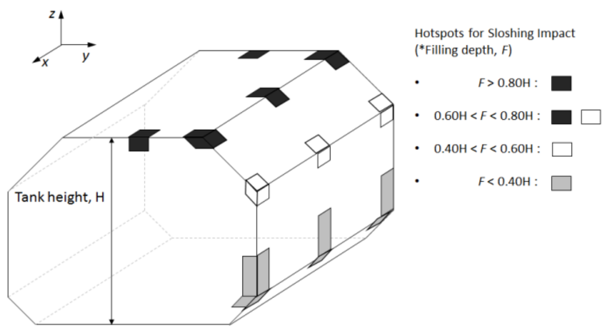

Figure 4: Example of hotspots of sloshing impact (membrane-type LNG cargo tank)

2.5.4 Data Acquisition System

The data acquisition system should be able to manage high sampling frequency data from multiple channels. The time histories of the measured pressure should be stored as raw data, and data filtering is not recommended during the data acquisition process. Signal processing should be carried out after preserving the raw data.

2.5.5 Measurement of Sloshing Flow

To see the global flow inside the tank, video recording is recommended during the model test. Recorded video enables double-checking the applied test conditions such as the liquid filling height, wave heading angle, and sea state. The video recorder should be positioned independent of the motion platform to allow the global tank motion to be captured.

If necessary, a high-speed camera can be used to determine the detailed local flow. For this purpose, the particle image velocimetry (PIV) method can be applied to visualize the local sloshing flow from a particular field of view (Lugni et al., 2009).

2.6 Data Analysis

Statistical post-processing is required to determine the characteristics of sloshing impacts that occur during the model testing. Data analysis can be categorized through the following steps:

- Numerical filtering of the raw pressure data
- Consideration of spatially averaged pressure, which can be regarded as the global load on a specified area.
- Identification of sloshing impacts from the time histories of measured pressure data and characterization of the identified impacts.
- Estimation of the statistical properties of the sloshing impacts.

2.6.1 Data Filtering

Raw pressure data may include hydrostatic pressure, low frequency pressure from waves, and other noises. If the tests are only interested in the impact pressure with a short impulse time, a high-pass filter can be used on the raw pressure data to eliminate the low-frequency pressure component. The cut-off frequency should be defined based on the response period of the sloshing event, structural eigen-frequencies, and the properties of the pressure sensor, among other elements. If the test data are numerically filtered during post-processing, the type of filter and filtering frequency should be reported.

2.6.2 Identifying Sloshing Peaks

The peak over threshold method can be used to identify a sloshing event from the time history of the measured pressure data (Figure 5). Initially, pressure peaks that exceed the pressure threshold value are to be extracted as temporal peaks. The threshold value should be sufficiently large to eliminate experimental noise, and should be smaller than the pressure maxima induced through sloshing events. Within a moving time window, the largest temporal peak is collected as the global sloshing peak. The sampling time window should be sufficiently wide to catch only one peak during a single sloshing event (a single sloshing event can bring about multiple pressure peaks, particularly for impact with gas entrapment). A series of sensitivity studies is recommended to find the appropriate time window size and the threshold level.

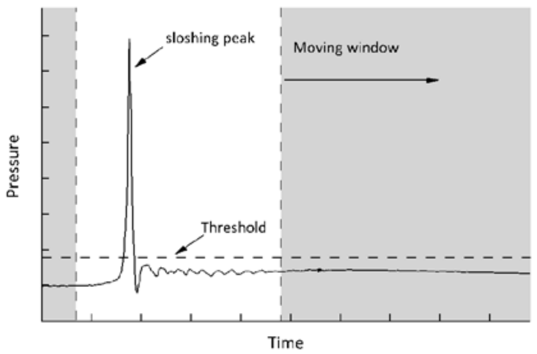

Figure 5: Identifying sloshing peaks (peak over threshold method)

The peak over threshold method does not need to be applied to the time history of a single pressure sensor. The moving time window can be applied to the pressure signals from multiple sensors positioned close together, or sensors located at the same cluster panel, or all sensors installed for the model testing. Using this process, only the maximum sloshing peak will be sampled for each sloshing event within the specified area.

Sampled peak pressure signals can be simply assumed as triangular in shape, and the characteristics of the peaks can be defined using certain parameters such as the peak pressure, rise time, decay time, and impulse area. The rise time is usually defined as twice the time taken from the moment half of the peak pressure occurs to the moment the peak pressure is reached. The decay time can also be defined in a similar way. An impulse area can be defined using a modelling parameter such as the peak pressure, rise time, and decay time, or in a numerical integration of the discrete pressure time history.

The number of sloshing impacts can be obtained from the peak sampling procedure. The response period can then be calculated by dividing the test duration by the number of identified impacts. The response period is used to estimate the number of sloshing events per specific duration, which is essential to estimating the extreme sloshing value of a particular return period.

2.6.3 Estimation of Extreme Sloshing Impact

To estimate the probable extreme pressure of a sloshing impact, the probability distribution of the sloshing impact should be established. All sampled sloshing impacts should be sorted with respect to the magnitude of the peak pressure. After sorting the sloshing peaks, a probability of exceedance (PE) curve of the sloshing impact can be estimated. For a large number of sloshing peaks, N, the probability of exceedance of sloshing peaks can be assumed as 1/(N+1).

The probability distribution of discrete sloshing peaks shall be fitted to the extreme distribution function (Figure 6). Commonly used mathematical functions include 3-parameter Weibull and Generalized Pareto. As curve fitting methods, the maximum likelihood estimation and method of moment are widely used. It is recommended to check how well the statistical model fits a set of measured sloshing peaks. Generally used goodness-of-fit tests conducted include a Chi-squared test, Kolmogorov-Smirnov, and a probability plot correlation coefficient test.

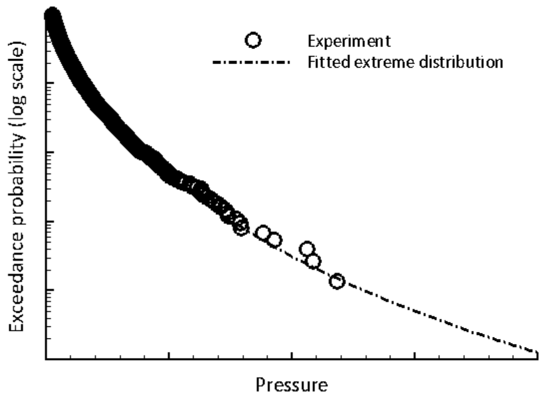

Figure 6: Exceedance probability distribution of sloshing impact pressure

When comparing the test results of various cases, a direct comparison of the PE curve may be difficult because each test has a different response period. In these cases, it is recommended to normalize the probability plots by dividing the exceedance probabilities by the response period of each case. Normalized PE curves then have the same probability levels irrespective of the return periods.

The probable extreme pressure can be estimated for various return periods using a fitted PE distribution. Owing to the slow convergence of the test results, an extrapolation of the model test data is not recommended. If model tests are conducted multiple times for identical test conditions, the test data should be preferably combined as one set in a statistical model.

Based on a fitted PE curve, other mathematical probability curves can be easily established, such as a probability density function (PDF) or cumulative density function (CDF).

2.6.4 Data Analysis for Multiple Pressure Sensors

Basically, the time history of a single pressure sensor represents the load acting on a small sensing area. To evaluate the sloshing loads on a relatively larger area, additional signal processing is required. The time history of the area load can be generated by averaging the pressure time histories of individual pressure sensors clustered at the region of interest. The generated spatially averaged signal can be considered an additional channel. However, special care is needed when applying a dynamic analysis of this averaged load.

2.7 Prediction of Design Loads

The procedure used for a sloshing model test is flexible in dealing with the test objectives. When a study is aimed at determining the design sloshing impact loads on a cargo containment system, either a short-term or a long-term analysis procedure is recommended.

2.7.1 Short-Term Approach

A short-term analysis is a series of processes determining the most critical navigation conditions for sloshing loads, and estimating an extreme load for a 3 h return period under these critical conditions. To find the critical navigation conditions, sloshing model tests should be carried out in three steps: 1) initial screening phase tests, 2) refined screening phase tests, and 3) design phase tests.

A short-term analysis can reduce the time cost for conducting the sloshing model test, but has less reliability.

Initial Screening Phase

In screening phase tests, the navigation conditions should be roughly covered. The navigation conditions can be expressed as a combination of the filling height, heading angle, wave period (Tz), wave height (Hs), and ship speed if necessary.

It is generally known that head/quartering sea conditions are critical for high filling conditions and that beam sea conditions are critical for low filling conditions.

It is recommend that the wave periods be covered with a discretization of at least 2 s, and the corresponding lifetime wave height be considered for each wave period. It should be noted that the most extreme sloshing may not occur under the most extreme sea state. In this case, the designed sloshing load should be determined based on a different return period, not a 3 h period.

By comparing the magnitude of extreme sloshing loads for a 3 h return period, several candidates for the critical navigation condition can be determined. To estimate the 3 h extreme pressure, a sufficient simulation time is required (at least 5 h).

Refined Screening Phase

During the refined screening phase, additional model tests are carried out around the critical conditions of the initial screening phase. Candidates of critical navigation conditions can be changed after the refined screening tests. In a general sense, extreme sloshing loads established from a single pressure sensor are much larger than the extreme load from spatially averaged load data. The difference in load area may also be considered when identifying the critical navigation conditions for the design phase process.

Design Phase

Based on the results from the screening phase, long duration tests should be carried out for candidates of critical navigation conditions. To obtain sufficient data for a reliable estimation of the designed sloshing load, at least a 30 h test duration is recommended. Long duration test data can be acquired by repeating the short duration model test. Although the same navigation conditions are considered, the time history of the tank motion should be unique for each repeated test. A unique motion history can be achieved by adopting random wave phase angles using an inverse Fourier transform method.

For each critical condition, 3 h maximum sloshing loads are estimated from long duration test data. It is recommended to estimate the 3 h maximum load from the accumulated data of a long duration test, rather than averaging the 3 h loads from short duration tests.

Finally, the navigation conditions that show the maximum 3 h sloshing pressure are regarded as the design conditions, and the corresponding sloshing pressure becomes the designed short-term pressure. This value is then regarded as the maximum pressure that a vessel is expected to experience once in a lifetime. In general, the design pressure evaluated from a short-term approach is significantly lower than the pressure estimated from a long-term analysis.

2.7.2 Long-Term Approach

A long-term distribution of the sloshing loads can be obtained by combining the model test results of the possible short-term sea states, which can represent all sea conditions the vessel will experience during its lifetime. Unlike a short-term approach, which only covers extreme sea states, a long-term approach requires model test data for a wide range of sea states covering an entire wave scatter diagram.

The long-term probability $Q(P)$ of exceeding the sloshing impact pressure P can be expressed as follows:

$$Q(P) = \sum_{k=1}^{\#Fillings} \sum_{j=1}^{\#Headings} \sum_{i=1}^{\#Sea\ States} p_{ijk} \cdot \frac{R_{ijk}}{R} Q_{ijk}(P)$$

where

p_{ijk} is the probability of navigating with filling height *k*, relative wave heading *j*, and sea state *i;*

R_{ijk} is the event rate (number of impacts per hour) of sloshing impacts identified from a sloshing model test with navigation conditions *i*, *j*, and *k*;

R is the average event rate based on all model test data; and

$Q_{ikj}(P)$ is the xceedance probability for sloshing impact pressure *P* under navigation conditions *i*, *j*, and *k*.

The probability of navigation condition p_{ijk} should be determined based on the wave scatter data and operational conditions. Other parameters such as R_{ijk}, R, and $Q_{ikj}(P)$ can be established from the model test.

In practical terms, it is difficult to apply every sea state presented in a wave scatter diagram. For this reason, the navigation conditions should be widely covered with an appropriate grouping of the sea states. Discretization of 45° for the wave heading, 2 s for the Tz, and 3 m for the Hs are recommended as the minimum values. Additional consideration may be needed near the tank resonance periods, which are closely related with the liquid filling height. The filling height conditions should be determined based on the type of vessel (some vessels have filling restrictions). At least a 5 h (real-scale) model test should be carried out for each navigation condition. If the test shows no sloshing impacts during a 30 min simulation (real scale), the corresponding conditions do not need to be continued to the end.

3. PARAMETERS TO BE TAKEN INTO ACCOUNT

The following parameters defining the tests should be taken into account (as applicable): Scale

- Model tank dimensions
- Ratios of model to tank dimensions
- Properties of fluids filled inside the model tank
- Liquid filling height
- Speeds and headings
- Wave characteristics
- (height, period, spectra,…)
- Ship motion RAO
- Tank arrangement (distance from COG of the ship,…)

- Accuracy of motion platform
- Run duration
- Number of runs per test condition
- Positions of pressure sensors
- Data sampling frequency
- Sensor calibrations and accuracy

4. VALIDATION

4.1 Benchmark Test

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