Structural Safety of IHI-SPB LNG Tanks against Sloshing

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The IHI-SPB tank is an excellent LNG tank for FLNG and LNG fuelled vessels, because it has high structural safety against sloshing. The high structural safety is achieved through a highly reliable design technique, backed up by many experiments and numerical simulations the result of which is the prevention of resonance between liquid motion and ship motion. This paper describes the necessity of avoiding such resonance and describes the numerical simulation of pressure induced by internal liquid motion using the Particle method, which is an advanced calculation technique.

1. Introduction

Recently, an energy shift from oil and coal, which have high greenhouse gas emissions per unit of produced heat, to natural gas, which has fewer greenhouse gas emissions, has been underway as one measure to counteract global warming. In response to the resulting increase in demand for natural gas, the development of offshore gas fields is being planned in various areas. For offshore gas field development, the use of Floating Liquefied Natural Gas (FLNG) facilities that product, store, and offload natural gas at sea is being planned. In addition, one example of the energy shift to natural gas is the ongoing development of LNG-fueled ships that use Liquefied Natural Gas (LNG) as marine fuel. The IHI-SPB tank is receiving attention as an LNG tank for use with these FLNG facilities and LNG-fueled ships, thanks to the structural safety of the IHI-SPB tank against sloshing. Sloshing generally refers to internal liquid motion that is produced due to the motion of the ship, but in a narrower sense, sloshing is the violent fluid motion produced when the ship motion and the internal liquid motion resonate with each other. In this article, the term "resonance sloshing" will be used to refer to the strong internal liquid motion produced when the ship motion and the internal liquid motion resonate with each other.

Anti-sloshing measures at intermediate liquid levels is one of the functions demanded of an LNG tank for an FLNG facility or LNG-fueled ship. On an LNG ship, resonance sloshing can be avoided by transporting the LNG tank in a full or empty state, but resonance sloshing becomes an unavoidable problem in an FLNG facility where the liquid level changes constantly as a result of LNG production and offloading, or an LNG-fueled ship where the liquid level changes as fuel is consumed. Since the needed performance against sloshing differs depending on the intended application of the LNG tank, it is necessary to design tanks according to each application.

The Self-supporting Prismatic-shape IMO type B tank (abbreviated IHI-SPB tank), was developed by JAPAN Marine United Corporation (JMU), and has high structural safety against sloshing thanks to the following features.

(1) Sloshing due to resonance between ship motion and internal liquid motion is prevented at arbitrary liquid levels by installing bulkheads inside the tank.
(2) Highly accurate estimation of the pressure induced by internal liquid motion, backed up by many experiments and computational simulations.

In the IHI-SPB tank, resonance sloshing is avoided by installing bulkheads inside the tank, and advanced analysis techniques backed up by experiment and computational simulation are used to estimate the sloshing load produced in the IHI-SPB tank. As a result, high structural safety against sloshing is achieved. At JMU, many IHI-SPB tanks have already been constructed for use as LNG tanks on carriers and Liquefied Petroleum Gas (LPG) tanks on carriers and floaters (FPSO & FSO), and damage to a cargo tank has yet to occur. They also include LNG ships that have been navigating the Alaskan route, said to be the severest shipping route in the world, for 18 years without avoiding intermediate liquid levels. This proves that the IHI-SPB tank has high structural safety against sloshing. This article will introduce the necessity of the resonance-avoiding design that is the source of the structural safety against sloshing in the IHI-SPB tank, as well as the simulation of loads due to internal liquid motion using the particle method, which is an advanced computational technique.

2. Necessity of avoiding resonance between internal liquid motion and ship motion

2.1 Relationship between internal liquid motion and ship motion

The natural period of internal liquid motion inside a tank is a function of the liquid depth and the tank width in the oscillation direction, as expressed in formula (1).

$$T = 2\pi\sqrt{\frac{l}{\pi g \tanh(\pi h / l)}} \quad \cdots\cdots (1)$$

T : Natural period (s)
h : Liquid depth (m)
l : Tank width in oscillation direction (m)
g : Gravitational constant (m/s^2)

Figure 1 illustrates the bulkhead arrangement in a typical size IHI-SPB tank used for FLNG (length × width × depth (m): 31 × 55 × 26). A transverse bulkhead and a longitudinal bulkhead are respectively provided in the center of the lengthwise direction and the widthwise direction, dividing the tank into four sections. **Figure 2** illustrates the natural periods of internal liquid motion and ship motion. The blue line indicates the relationship between the natural motion of the internal liquid motion and the liquid level in the tank. Also, for reference, the red line indicates the relationship between the natural period of the internal liquid motion and the liquid level when there are no bulkheads (no internal structures). The green area indicates the natural period of the ship motion of a typical FLNG facility. **Figure 2** demonstrates that for the IHI-SPB tank, the natural period of internal liquid motion for all liquid levels is sufficiently separated from the natural period of ship motion, whereas for a tank without internal structures, the natural period of the internal liquid motion and the natural period of ship motion overlap at liquid levels from 10% to 20%.

2.2 Internal liquid motion in resonance and non-resonance conditions

A model of the IHI-SPB tank illustrated in **Fig. 1** and another model without internal structures were used to simulate internal liquid motion when the tanks are oscillated under the conditions indicated in **Table 1** by computational fluid dynamics analysis (FLOW-3D: commercial CFD software). In the computational simulation, only the liquid phase was modeled without modeling the vapor phase, and the tank interior was discretized into cubes with an average edge length of 300 mm. **Figure 3** illustrates the liquid motion inside the IHI-SPB tank. **Figure 3** demonstrates that in the IHI-SPB tank, resonance sloshing does not occur, and the internal liquid motion is calm.

Figure 4 illustrates the internal liquid motion in the model without internal structures. **Figure 4** demonstrates that in the model without internal structures, resonance sloshing is produced, causing strong non-linear phenomena such as breaking waves at the free surface, high-speed collisions of

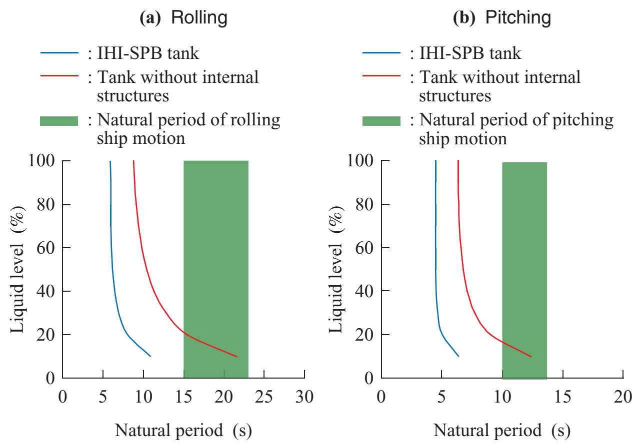


Fig. 2 Natural period of liquid motion and ship motion

Table 1 Computational conditions

Item	Unit	Condition
Oscillation	—	Rolling
Amplitude	Degree	10
Period	s	18
Level	%	15 (4)*1

(Note) *1: Indicates level (m) at 15%

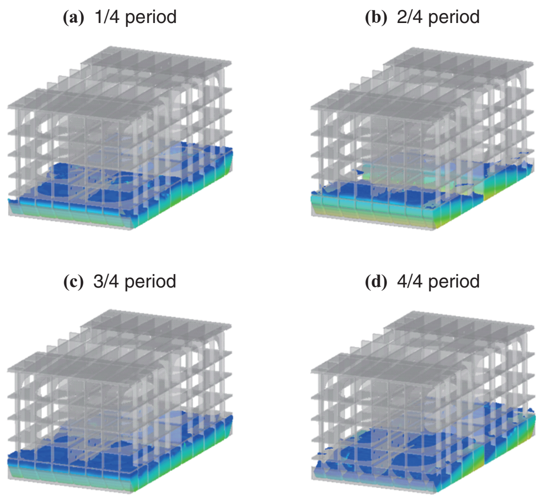


Fig. 3 Liquid movement in IHI-SPB tank

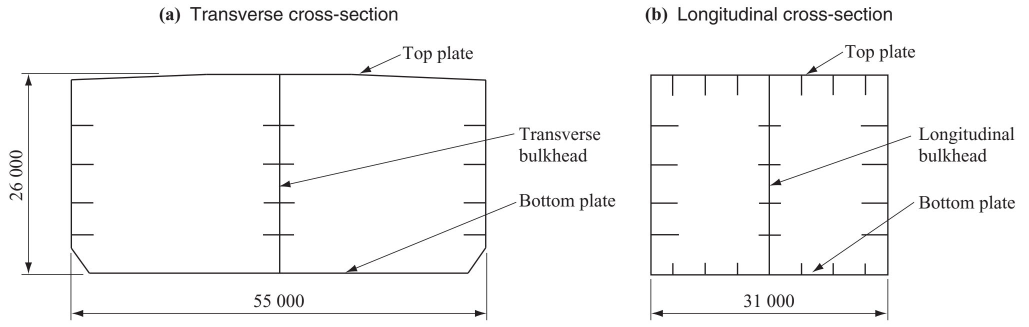


Fig. 1 Bulkhead arrangement of IHI-SPB tank (unit:mm)

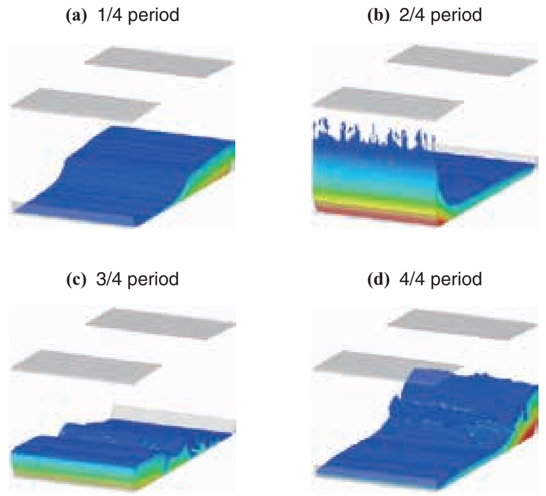
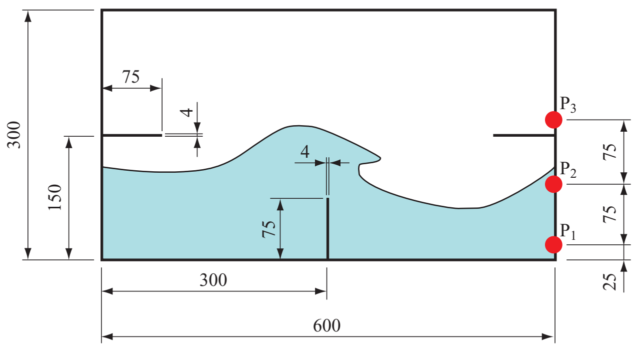


Fig. 4 Liquid movement in the tank without internal structure

liquid against the tank sides, and jet flows. Estimating the sloshing load when such violent internal liquid motion occurs is thought to require consideration of these strong non-linear phenomena, as well as consideration of the effects of bumping when LNG collides with the walls, and the structure-fluid interactions.(1) Although there have been many attempts to estimate the sloshing load during resonance through many experiments and computational simulations,(2), (3) a definitive solution has not been obtained at present.

2.3 Loads on internal structures in resonance and non-resonance conditions

From the sloshing experiment results obtained using the two-dimensional model tank illustrated in **Fig. 5**, the loads produced on internal structures in resonance and non-resonance conditions were compared. The two cases indicated in **Table 2** are representative resonance and non-resonance conditions, and all parameters other than the period take the same values. **Figure 6** illustrates internal liquid motion in the resonance and non-resonance conditions, while **Fig. 7** illustrates a pressure time history at pressure computation point P_2. From **Fig. 7**, the maximum pressure during non-resonance is approximately 450 Pa, while the maximum pressure during resonance is approximately 1 740 Pa, thereby demonstrating that the maximum pressure during resonance is approximately four times the maximum pressure during non-resonance.



(Note) P_1, P_2, P_3 : Pressure computation points

Fig. 5 Section view of 2-dimensional model tank (unit:mm)

3. Simulation of internal liquid motion-induced load using particle method

Since it is difficult to estimate the sloshing load produced when the ship motion and internal liquid motion resonates, and since the load itself is so much larger than that in the non-resonance condition, the IHI-SPB tank is designed to avoid resonance, as described in **Section 2**. Consequently, **Section 3** will introduce an example of an advanced computational technique, the particle method, which we used to simulate the load induced by the calm internal liquid motion produced inside the IHI-SPB tank.

In the past, a grid-based numerical computation (FLOW-3D) was used to simulate the load induced by internal liquid motion on the IHI-SPB tank. However, there was a problem in that the calculation would produce unrealistic solutions, such as the occurrence of unnatural pulses of pressure, when calculating the impact pressure produced when fluid collides into the horizontal girders or sides.(3) To avoid this, the particle method(4) was used instead. The particle method enables easy tracking of the free surface, and its application to the sloshing problem is being tested. Herein, we report our findings from a comparison of particle method computational results with the results of a large-scale model test. The particle method computational tool used was the

Table 2 Experimental conditions

Item	Unit	Condition	
		Resonance	Non-resonance
Amplitude	mm	50	50
Period	s	0.75	1.5
Level	mm	100	100

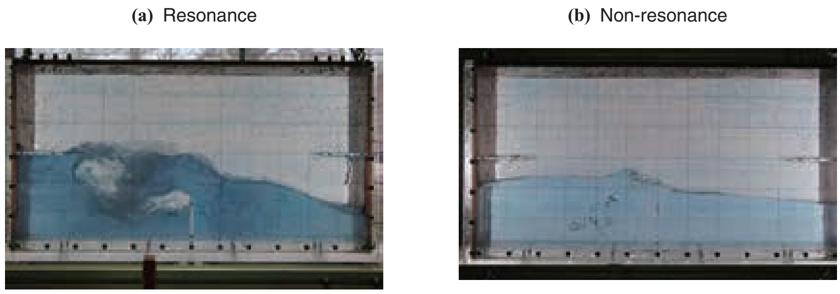


Fig. 6 Liquid movement in resonance and non-resonance condition

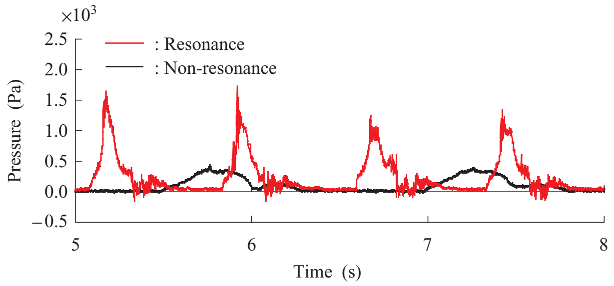


Fig. 7 Pressure time history at P_2 in resonance and non-resonance condition

commercial particle method software Particle Works.

3.1 Large-scale model test

Sloshing experiments were conducted using a 1/10 scale model of the IHI-SPB tank. However, the modeling range was taken to be a 1/8 section obtained by vertically halving the 1/4 section partitioned by the transverse bulkhead and the longitudinal bulkhead. As illustrated in **Fig. 8**, the dimensions of the model tank include a length of 1 600 mm, a width of 2 700 mm, and a depth of 1 200 mm. For the internal structures, only the horizontal girder, transverse web frame, and vertical web frame were modeled. Small structures like stiffeners and support structures were not modeled. Pressure gauges were installed under the surface of the horizontal girder and walls, where impact pressure due to internal liquid motion readily occurs.

3.2 Comparison of computational and experimental results

Under the conditions shown in **Table 3**, the pressure time history results at point A under the surface of the horizontal girder was compared for the particle method and the large-scale model experiment (see **Fig. 8**). In addition, a similar computation was also conducted using the grid method (FLOW-3D) for comparison with the particle method. In both the particle method and the grid method, the gas phase was not modeled, only the liquid phase. In the particle method, the fluid region was discretized using a particle diameter of 20 mm, while in the grid method, the space inside the tank was discretized into cubes with an average edge length of 20 mm.

Figure 9 illustrates a still image of the experiment and a still image from the particle method computation. **Figure 9** demonstrates that liquid motion is calm and complex non-linear phenomena do not occur. **Figures 10** and **11** illustrate pressure time histories at point A (see **Fig. 8**) derived from the computational results of the particle method and the grid method, and from the large-scale model test.

Figures 10 and **11** demonstrate that with the particle method, impact pressure peak values, durations, and impulses match well with experimental results. On the other hand, with the grid method, unnatural pulses of pressure not seen in the experimental results are produced, demonstrating that the impact pressure is not accurately simulated.

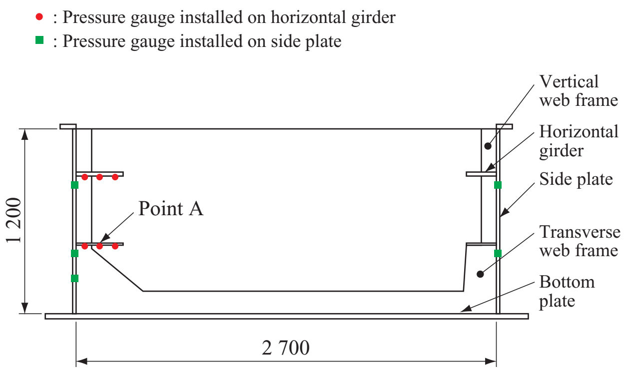


Fig. 8 Section view of large-scale model tank (unit:mm)

Table 3 Experimental and computational conditions

Item	Unit	Condition
Oscillation	—	Rolling
Amplitude	Degree	1.5
Period	s	2.82
Level	mm	400

4. Conclusion

This article introduced the necessity of resonance-avoiding design that is essential for securing structural safety against sloshing in the IHI-SPB tank, as well as the simulation of loads due to internal liquid motion using the particle method. The conclusions are as follows.

(1) Because of the internal bulkheads, the IHI-SPB tank is able to avoid resonance sloshing.

(2) Resonance between ship motion and internal liquid motion creates violent internal liquid motion. The sloshing load produced at this point has a value several times larger than that in a non-resonance condition, and

(a) Large-scale model test

(b) Particle method

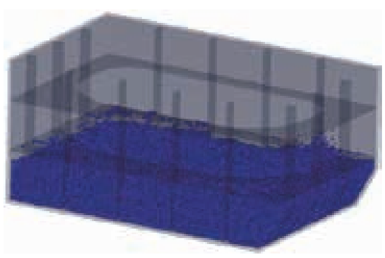


Fig. 9 Liquid movement of large-scale model test and computation

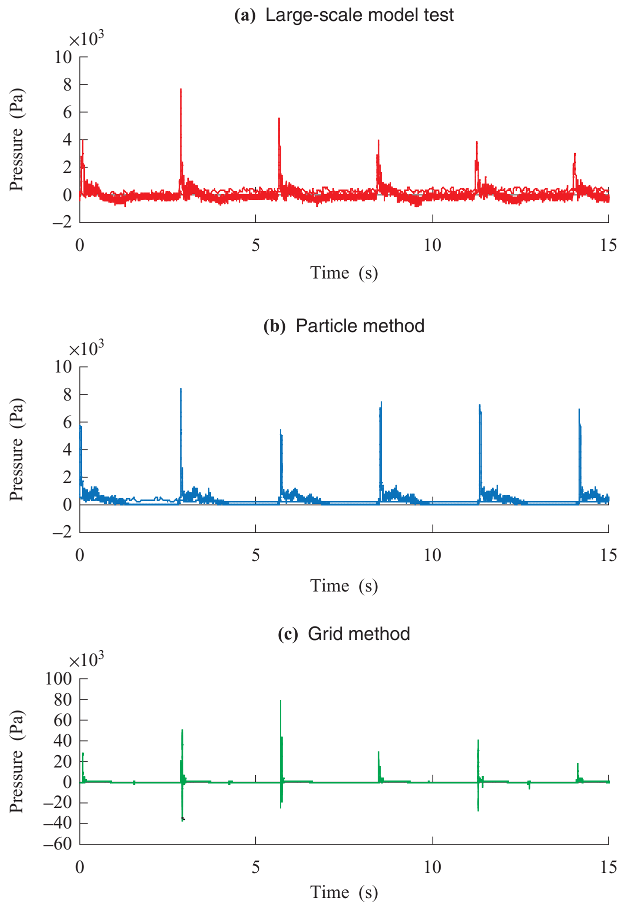


Fig. 10 Pressure time history derived from large-scale model test and computations

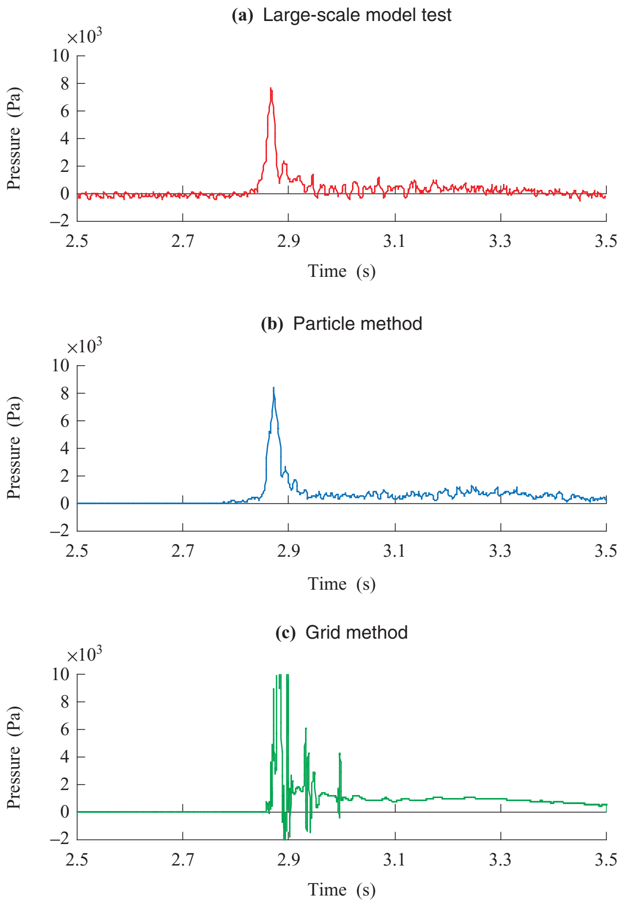


Fig. 11 Detailed pressure shape derived from large-scale model test and computations

estimation of the load is crucial. However, estimating the load of such sloshing requires consideration of complex non-linear phenomena, and estimation by experimentation and numerical computation is considered to be difficult at present.

(3) Under conditions in which the ship motion and the internal liquid motion do not resonate, the internal liquid motion is calm and complex non-linear phenomena do not occur. Also, the load induced by the calm internal liquid motion at this point is sufficiently small compared to the sloshing load in the resonance condition.

(4) The particle method is able to accurately simulate the impact pressure produced during calm internal liquid motion. The unnatural pulses of pressure seen in the grid method do not occur in the particle method computational results, and peak values, durations, and impulses all show good agreement with experimental results.

By installing bulkheads inside the IHI-SPB tank, resonance sloshing is avoided. And high structural reliability is achieved by using advanced analysis techniques backed up by experiment and numerical computation to estimate with high accuracy the load induced by internal liquid motion and eliminating to the maximum extent possible uncertain elements in the design.

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