International Journal of Ocean Engineering and Technology Vol. 5, No. 1, pp 22~28, December 2002 (ISSN 1229-1668)

Motion and Sloshing Analysis for New Concept of Offshore Storage Unit

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(Received 26 November 2001, accepted 17 January 2002)

ABSTRACT: *A New concept for the LNG-FPSO ship, with moonpool and bilge step in bottom, is proposed. This concept is investigated with regard to motion reduction and sloshing phenomena of the cargo and operation tanks. The principal dimensions of the ship are* $L \times B \times D \times t(design) = 270.0 \times 51.0 \times 32.32 \times 13.7(m)$, *with a total cargo capacity of 161KT; a 98% loading condition is considered for this study. The Two moonpools and rectangular step at the bilge have been designed for the purpose of decreasing the motion within the tanks.*

For the motion analysis, linearized three-dimensional diffraction theory, with the simplified boundary condition, was used. The six-degree of freedom coupled motion responses were calculated for the LNG-FPSO ship. Viscous effects on the roll motion responses of a vessel were taken into account in this calculation program, using an empirical formula suggested by Himeno(1981).

The case study for the moonpool size has been conducted using theoretical estimation and the experimental method. For the optimization of the moonpool size and effect of the bilge step, 9 cases of its size, both with and without bilge step, were involved in the study. The motion responses, especially roll motion, for the designed LNG-FPSO ships are much lower than those of other drill ships and shuttle tankers. The limit criterions are satisfied.

To check the cargo tank and operation tank sizes, we performed a sloshing analysis in the irregular waves which focuses on the pressure distribution on the tank wall and the time history of pressure and free surface for No.2 and 5 tanks of LNG-FPSO with chamfers. Finally, optimum tank size was estimated.

KEY WORDS: LNG-FPSO, Moonpool, Bilge Step, Roll Motion, Sloshing

1. Introduction

Currently, many governments in the world have emphasized LNG (Liquefied Natural Gas) as a clean energy, and are concerned with furthering the use of this type of gas. Much of the natural gas has been flared in the oil and gas field, despite the economical and environmental loss. Many oil companies have interest in the collection of gas and development of the marginal field. The LNG-FPSO development between oil companies and consulting company has been discussed since the 1990s, but has never come to fruition.

Samsung Heavy Industries (SHI) has expressed much interest in it, and created concept designs for the new FPSO hull shape which is focused on the reduction of roll motion in the beam sea. From the study of drilling vessel "NAVIS Explore I", we are convinced that the ship has a distinguished motion performance, that is result of the design of the moonpool and bilge step in the hull body.

The concept design of LNG-FPSO is also focused on the adoption of similar system. The moonpools are located in the aft and fore body along the midship centerline. This ship also adopted steps on both sides of the bilge as in a underlay of the shoe. The ship has 161KT cargo capacity, one set azimuth thruster, and a GTT Mark-III membrane cargo containment system.

Motion performance, specially rolling, is one of the very important performances in the FPSO structure, because of the structural safety of the unloading system. Chaplin and Ikeda(1999) studied the effects of viscosity on forces and motion responses of offshore structures and floating bodies.

In the design of LNG related ship, sloshing analysis in the cargo tank is a required process for the check of hydrodynamic loads on the tank wall. Paik and Ha (1998) analyzed the sloshing phenomena for the cargo tank of the 138K LNG carrier. For the check of validity of cargo and operating tank dimensions in this developing LNG-FPSO, an operating tank and a cargo tank are selected. The sloshing simulation program in SHI solves N-S equations and uses the VOF(volume of fluid) algorithm, which accurately exprresses the nonlinear motion of fluid.

2. Concept Design of 161KT LNG-FPSO

The basic scheme of the LNG-FPSO is based on the 138KT LNG carrier, which is operated by K0.orea Gas Company.

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The topside of the process plant on deck is assumed to be supplied by the owner, and is not included in this general arrangement. However, the lightweight of the topside is estimated at about 17,000MT, based on the building experience of FPSO. The principal dimensions of the design ship is shown in Table 1. The FPSO has 4 operating tanks at both sides of the two moonpools, and has 3 LNG cargo tanks. The total cargo capacity, at 98% tank loading, is 161,000 m^3.

Table 1 Principal dimensions

Particulars	Dimensions
Length over all	278.0 m
Length between perp.	270.0 m
Breadth	51.0 m
Draft at design/scantling	13.0/14.5 m
Displacement at Td	162,140 m^3

Table 2 Cases of moonpool shape and step for calculation

Case No.	Moonpool L×B = Area (unit : m)	Step	Remark
1	w/o	w/o	-
2	w/o	w/	-
3	19.465 x 12.32 = 239.809(A/2)	w/	m.p. 1
4	38.930 x 12.30 = 479.618(A)	w/	m.p. 2
5	58.395 x 12.30 = 719.426(3A/2)	w/	m.p. 3
6	38.930 x 6.16 = 239.235(A/2)	w/	m.p. 4
7	38.930 x 24.64 = 959.235(2A)	w/	m.p. 5
8	58.395 x 24.64 =1438.853(3A)	w/	m.p. 6
9	58.395 x 24.64 =1438.853(3A)	w/o	m.p. 6

To decrease the ship motion RAOs, especially rolling, the adoption of the bilge step and moonpool are considered. The effects of moonpool size and bilge step on ship motion are investigated, as shown in Table 2. The motion analysis is carried out on those 9 cases of the variation by theoretical calculation and experiment. The change of displacement is consistent with the moonpool size variation, but is ignored in this research because of its small quantity. Finally, the draught of the ship, for all cases of calculation and experiment, are fixed for the consistent comparison of motion performance.

3. Motion Calculation and Experiment

The ship motion calculation program is based on the 3-D panel method, and is applicable to mono and/or twin hull vessels, with or without forward speed. For further details of theoretical formulation and validation of the program, refer to the published paper (Kim *et al*, 1997). The 6-degree of freedom coupled motion responses are calculated for the LNG-FPSO.

Potential theory is based on the ideal fluid assumptions, so, all damping effects are attributed to wave making damping. This provides adequate results, except for rolling motion, for most of the oscillation modes of monohull ships; so, the viscous effect must be considered for the rolling effect. The viscous effects on the roll damping can generally be divided into four parts: skin friction, eddy making, hull lifting, and bilge keel damping components. In these calculations, most of the viscous component were considered, except bilge keel damping.

The ship is represented by a number of quadrilateral panels for the hull surface. Using a symmetry property, it was found that 200 panels, or more than half of the surface, provide a converged solution. Fig. 1 shows the example of the various panel arrangement, with 300 more panels for the half of the ship hull surface, which is used for the present calculations.

To reduce the extreme roll motion of FPSO, hull bottom shape is designed similar to the Navy's drill ship, as shown on Fig. 2, Table 2 and Fig. 3. The standard design of the LNG-FPSO is moonpool 2.

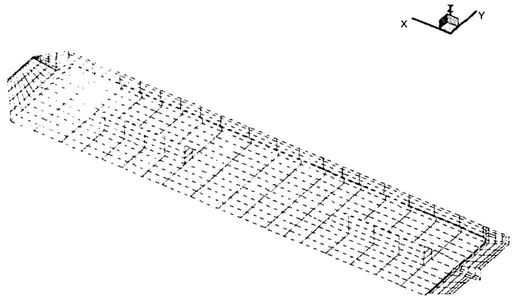

Fig. 1 Panel arrangement of FPSO

Fig. 2 The shapes of midship section

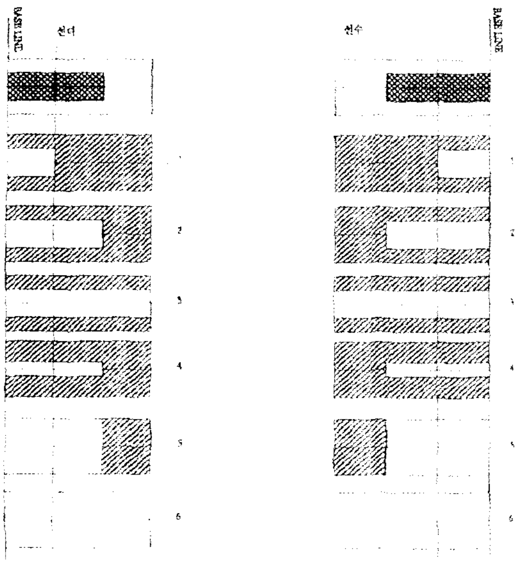

Fig. 3 The various moonpool types of FPSO

For the comparison of moopool size effect of the roll motion, the length and beam are changed. It is expected that the roll motion of the designed LNG-FPSO is significantly lower than the standard ship, due to moonpool and bilge step effect.

For the analysis of the tank dimension propriety, the roll and pitch motion trends are the focused on, in this paper. Figs. 4 and 5 show the roll and pitch RAOs vs wave frequency of the FPSO for all cases, as seen in Table 2, at zero forward speed. Consequently, in the high frequency range, the roll and pitch motions approach zero. In the case of the ship with bilge step and without moonpool, like the Navy's drill ship, the roll RAO has the maximum peak value 0.76deg/m and 20.0second of period in beam seas. In the case of the ship without bilge step and moonpool, like the general FPSO, the roll motion is 0.9deg/m which is slightly higher than the previous case. Roll motion of the designed LNG-FPSO is much lower at zero forward speed, compared to other ocean going ships. The roll RAO has the peak value about 0.58 deg/m and 20.0second of period and is significantly reduced, compared to ships without the moonpool. The effect of length and beam of the moonpool is investigated in the cases of moonpool 1 to 6.

The maximum pitch RAO occurs in the case, with bilge step and without moonpool, at bow quartering seas ($\beta=150^{\circ}$). The peak value is 1.0 deg/m at the center of gravity of the ship with zero forward speed. This is slightly larger than other moonpool cases, without bilge step.

Figs. 6 and 7 are the results of model tests for the roll and pitch motion. Model tests are carried out in the towing tank at Pusan National University, using a 2m model. These measured results show similar trends.

Figs. 8, 9, 10 and 11 show the calculated maximum value of roll and pitch amplitudes vs moonpool size variation, respectively. For comparison, maximum roll RAOs are plotted in Fig. 8.

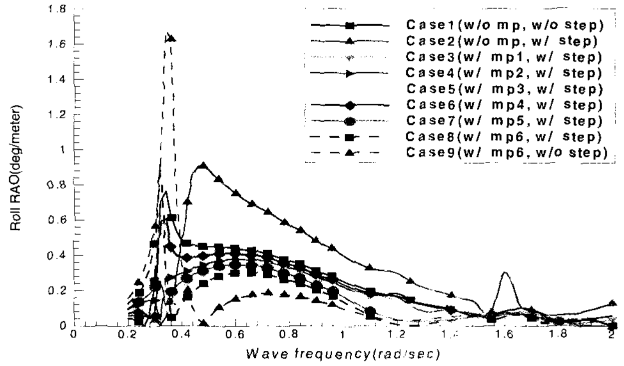

Fig. 4 Roll motion RAO in Beam seas (Cal.)

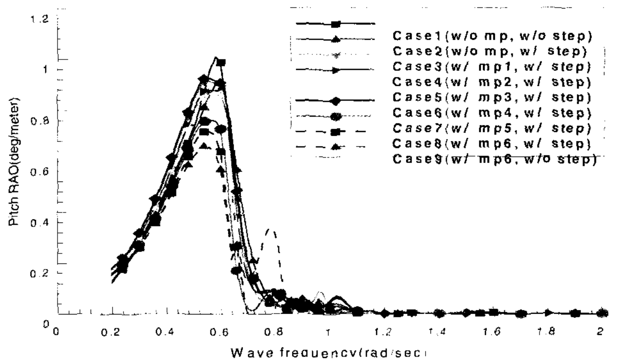

Fig. 5 Pitch motion RAO in Bow seas (Cal.)

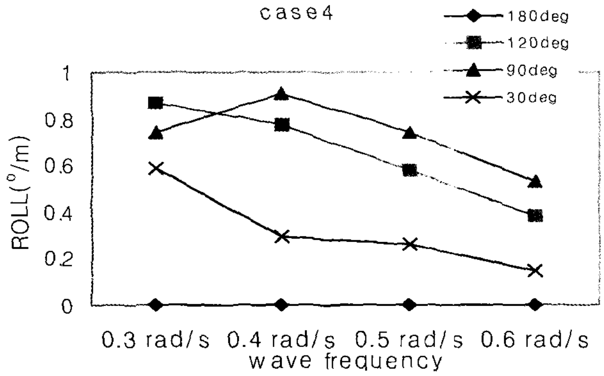

Fig. 6 Roll RAO (Experiment)

From these configuration of roll maximum value which are classified by heading angles at upper parts of these figures, all of the roll RAOs of LNG-FPSO are under 1.0

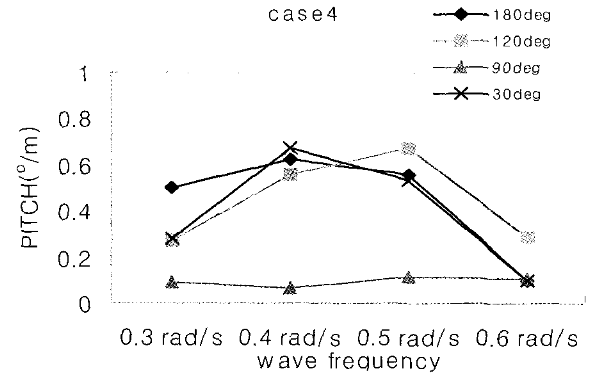

Fig. 7 Pitch RAO (Experiment)

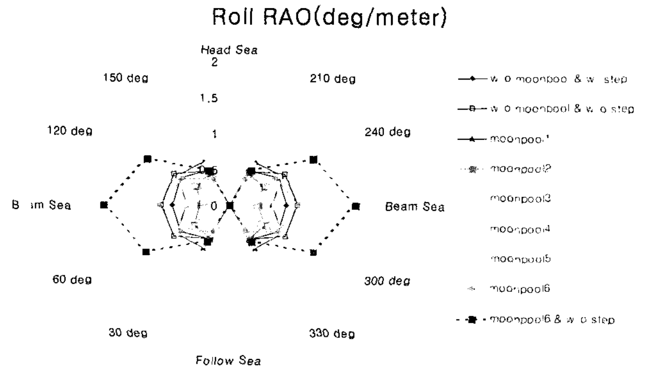

Fig. 8 Roll maximum amplitudes (Cal.)

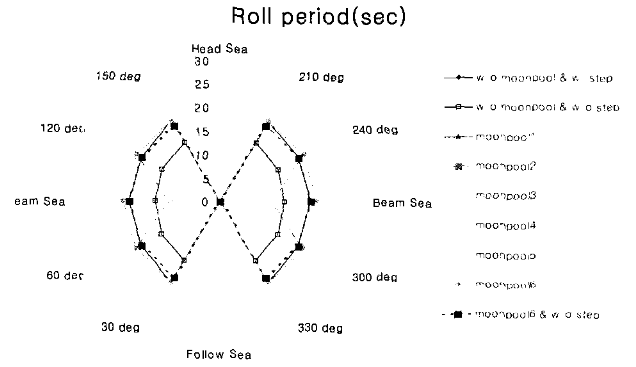

Fig. 9 Roll maximum periods (Cal.)

eg except moonpool 6 and without step. Due to moonpool ffects, the roll period are shifted at beam seas. Fig. 10 hows the maximum pitch RAO and period, classified by eading angles. All of the pitch RAOs of LNG-FPSO are nder 1.0 deg/m, except the case of without moonpool and vith step. Unlike maximum roll periods, maximum pitch eriods are not shifted at any heading angles.

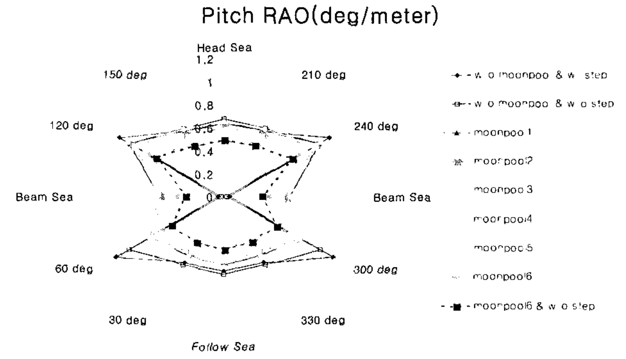

Fig. 10 Pitch maximum amplitudes (Cal.)

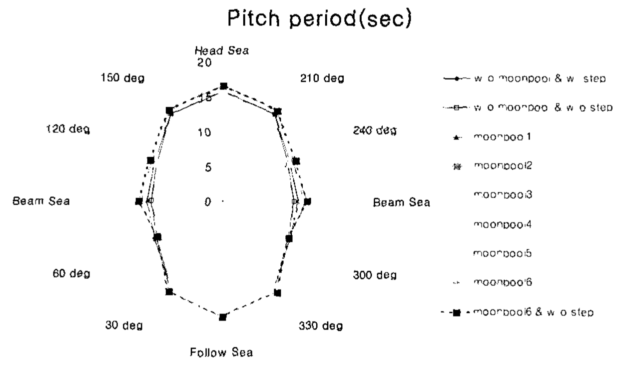

Fig. 11 Pitch maximum periods (Cal.)

4. Sloshing Analysis

Sloshing impact load is as important external force to be considered in the design of an LNG tank for LNG-FPSO. This impact force varies with the ship motion, tank shape, and liquid level. The relation between the period of ship motion and the natural period of liquid motion in LNG tank greatly effects the sloshing load on the LNG tank wall. The sloshing analysis becomes a very important procedure for the design of the LNG tank, because of the damage due to severe sloshing loads on LNG tank walls which may result in very dangerous situations.

We have chosen the no. 2 and no. 5 cargo tanks for the sloshing analysis, because the no. 5 tank has the longest distance between the cargo tank center and the LCG of the ship, and the dimensions of the no. 2 cargo tank are much larger than the others. The port side tank the no. 5 cargo tank is also chosen because of its symmetric geometry. In this case, we investigate the sloshing effect for the port side tank of the no. 5 and the no. 2 cargo tanks.

For the sloshing simulation, SHI has developed the CFD (Computational Fluid Dynamics) code, since 1994. The simulation program can calculate the dynamic motion of flow in three-dimensions. The code can solve the Navier-Stokes equations, and uses a VOF (Volume of Fluid) algorithm which can accurately express the nonlinear motion of fluid.

To investigate the sloshing effect in the no. 2 and no. 5 tanks, SHI has checked two points. The first is the possibility of resonance in the natural period of ship motion *and sloshing in the no. 2 and no. 5 tanks. The second is* the sloshing simulation and impact pressure in the irregular motion/waves in relation to the filling ratio of the tank. Table 3 shows the principal dimensions of the no. 2 and no. 5 tanks.

The natural period of pitch motion can be estimated using an empirical formula proposed by the several class rules, and shows the difference as the loading conditions. The pitch period of liquid motion can also be calculated using the eq. (1). The liquid motion period in the longitudinal direction is governed by the longitudinal shape of tank.

$$T=\sqrt{\frac{4\pi L}{g\cdot\tanh(h\pi/L)}} \tag{1}$$

The difference between the ship's natural period (10% fill departure condition) and the tank's natural period is within 3 seconds (LR's rule). Thus it is expected that the resonance may occur in all fillings of the no. 2/no. 5 LNG tanks, as shown in the Table 4. It is required to analyze sloshing effects for all fillings of the no. 2/no. 5 LNG tanks.

Table 3 Dimension of LNG tank No. 2 and No. 5

Tank	Dimensions(unit : m) (L×B×d)	Remark
No. 2	36.265×42.76×26.86	cargo
No. 5(port)	36.265×14.92×26.86	operating

Table 4 Natural periods of No. 2, No. 5 and storage unit

Filling (%)	Roll Period(sec)		Pitch Period(sec)	Remark
	No. 2	No. 5	No. 2/5	
10	15.1	4.44	14.3	
20	11.5	4.30	10.4	
30	9.89	4.34	8.78	
40	8.97	4.36	7.98	
50	8.42	4.37	7.53	
60	7.84	4.37	7.09	
70	7.70	4.37	6.99	
80	7.60	4.37	6.92	
Ship	27.35(scantling)		12.19(s)	LR
	11.89(10% loading)		8.09(b)	

The roll period of liquid motion in a tank can be estimated using the formula proposed by the class which is based on the potential theory. The period of liquid motion in a tank can also be estimated using the formula proposed by the class, which is based on the potential theory.

$$T=\sqrt{\frac{4\pi B}{g\cdot\tanh(h\pi/B)}} \tag{2}$$

The calculated natural periods are shown in Table 4. The difference between the ship's natural period (10% fill departure condition) and the tank's natural period have to be smaller than 5 seconds (LR's rule). Thus, in the roll motion, the possibility of resonance will be large. We have discussed the sloshing effects due to roll motion in the irregular waves.

The oceangoing ship is actually encountering the long-crested or short-crested irregular waves from place to place, depending on the sea state. In this paper, the actual motion of the vessel is estimated from the theoretically estimated RAOs of the ship. The actual waves which the LNG-FPSO will operate at, is assumed to be the ITTC standard wave spectrum as shown in eq. (3)

$$S(\omega_w)=\frac{173.0H_{1/3}^2/T_1^4}{\omega_w^5}\,\mathrm{EXP}\left(\frac{-691.0/T_1^4}{\omega_w^4}\right) \tag{3}$$

When a ship with mean forward speed V is navigating on a sea expressed as a wave spectrum, the ship recognizes the spectrum in terms of the encountering frequencies expressed as the following formula :

$$S(\omega_e)=S(\omega_w)\frac{1}{1-(2\omega_w V/g)\cos\mu} \tag{4}$$

The spectral density function of the ship response in the irregular sea surface is equal to the product of the spectral density function of waves and the response amplitude operator $H(\omega_e,\theta)$.

$$S_\phi(\omega_e)=\int_e S(\omega_e)\cdot G(\theta)|H(\omega_e,\theta)|^2 de \tag{5}$$

Eq. (5) is a frequency domain function and can be transformed to a function of time. $G(\theta)$ is the directional wave spreading function. The time history of the ship motion in 6-DOF can be estimated from the following Eq.;

$$\eta_j(t)=\lim_{n\to\infty}\sum_{i=1}^{n}\cos\{\omega_i t+\varepsilon(\omega_i)\}\sqrt{S_j(\omega_i)\delta\omega} \tag{6}$$

j=1,2,3,4,5,6 ; surge, sway, heave, roll, pitch, yaw

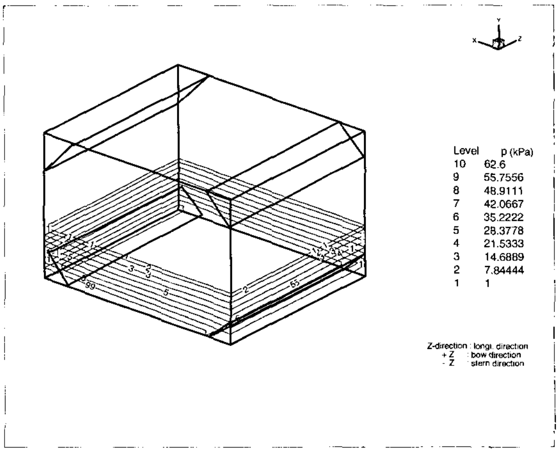

Fig. 12 Max. pressure of No.2 tank in 40% filling(beam)

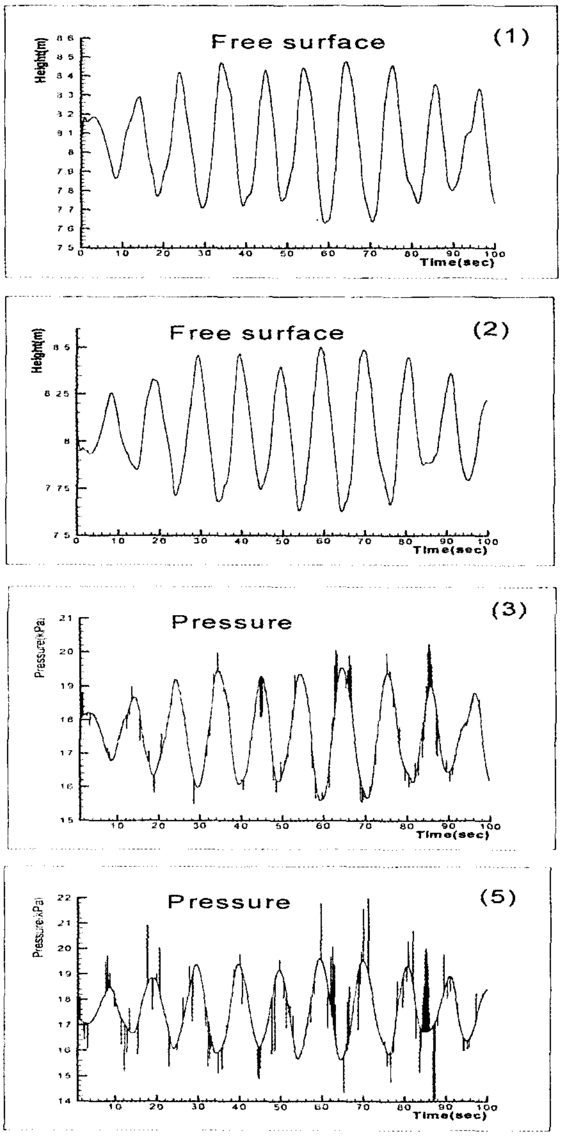

Fig. 13 Time history of No.2 tank in 40% filling(beam)

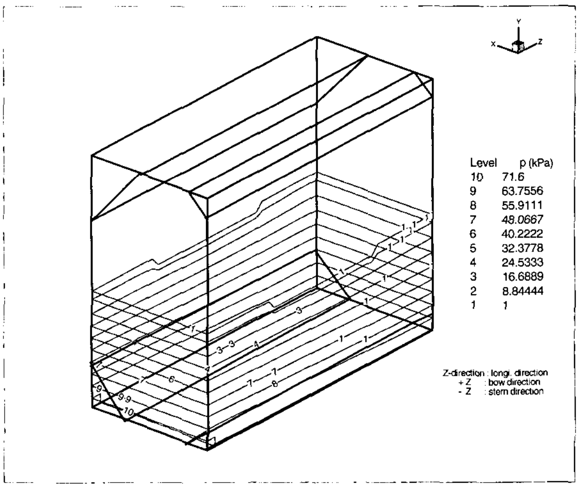

Fig. 14 Max. pressure of No.5 tank in 40% filling(bow)

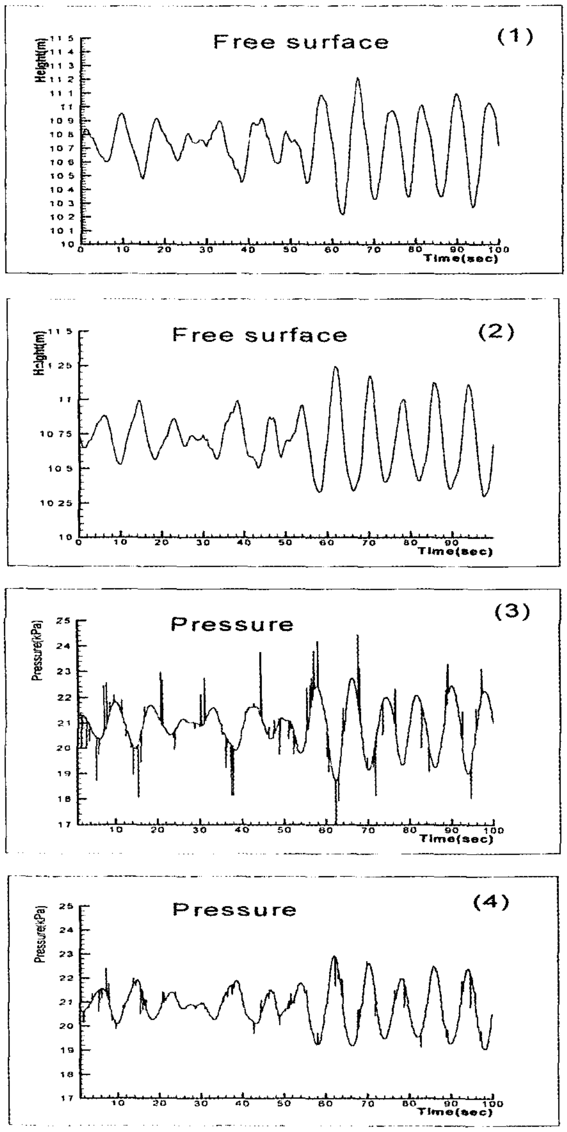

Fig. 15 Time history of No.5 tank in 40% filling(bow)

These time history data of motions are used as the input data for the sloshing simulation of LNG-FPSO in the irregular waves.

The calculating conditions were that $H_{1/3}$=12m (BN= 7), T_1=10.35 sec. (bow quartering sea), 11.56 sec.(beam sea), ship speed=0 Kts and all fillings. T_1 values are based on the tank natural frequency in low fillings (10% ~30%). The possibility of resonance between ship and tank is very high in low fillings. Pitch motions in bow quartering seas were considered for the sloshing analysis of the no. 5 cargo tank, because pitch RAO in bow quartering (120 deg.) is the largest. Roll motions in a beam sea were considered for sloshing analysis of the no. 2 cargo tank, because roll RAO in beam seas (90 deg.) is the largest.

We have produced time histories of motions by using wave spectrums eqs. (3), (4), (5) and ship motion RAOs. Figs. 12, 14 to show the maximum pressure on the wall, and Figs. 13, 15 to show free surface and pressure detect positions of no. 2 and no. 5 cargo tank model. The sloshing analysis has been performed for the no. 5 and no. 2 cargo tanks with chamfer in the condition of irregular waves. Maximum sloshing pressure of No. 2, 5 tanks are shown in Table 5. There is no impact pressure, and the pressure value is about 0.2~1.5bars in all cases of filling.

Table 5 Maximum sloshing pressure of No. 2, No. 5 tanks

Filling (%)	Max. pressure(bar)		Remark
	No. 2	No. 5	
10	0.27	0.28	no impact
20	0.44	0.41	no impact
30	0.62	0.55	no impact
40	0.78	0.71	no impact
50	0.91	0.87	no impact
60	1.15	1.03	no impact
70	1.33	1.18	no impact
80	1.48	1.34	no impact
90	1.53	1.47	no impact

5. Discussion and Conclusions

A feasibility study of LNG-FPSO which is conceptually designed by SHI is carried out. The investigation is focused on the motion characteristics and sloshing viewpoint. The motion estimation of the designed ship is theoretically carried out according to the with or without bilge step and various moonpool sizes. For reducing the roll motion of the FPSO, the adoption of the bilge step is very useful. However, basesd on this syudy, the effect of the moonpool is not significant.

For the check resonance between the ship motion and the fluid motion in cargo and operating tanks, we have confirmed that there is no resonance, and we have confirmed the tank dimensions. Sloshing analysis in the irregular waves has been performed. It focuses on the pressure distribution on the tank wall and the time history of pressure/free surface for the no. 2, no. 5 cargo tanks of LNG-FPSO with chamfers. From these sloshing studies, we can infer the following:

(1) Resonance and filling ratio of the no. 5 cargo tank (bow quartering sea) : There is no resonance and no impact pressures at all fillings levels.
(2) Resonance and filling ratio of the no. 2 cargo tank (beam sea) : There is no resonance and no impact pressure at all filling levels.
(3) Structural viewpoint : Reinforcement or structural analysis of the no. 2/no. 5 cargo tanks will not be required.

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