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Motion and Sloshing Analysis for New Concept of Offshore Storage Unit

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요 약: 본 논문에서는 선체 하부에 moonpool과 bilge step을 장착한 새로운 개념의 LNG-FPSO를 운동감소와 cargo, operation tank의 슬로싱 현상의 관점에서 기술하였다. LNG-FPSO의 주요제원은 L×B×D×t(design)=270.0×51.0×32.32×13.7(m) 이고 적용 조건은 total cargo capacity of 161KT at 98% loading condition 이다. LNG-FPSO의 운동감소의 목적으로 2개의 moonpool과 선체 하부 bilge 부분에 사각 step을 장착하였다.

LNG-FPSO의 운동해석을 위해 단순화된 경계조건을 만족하는 선형화된 3차원 diffraction theory를 사용하였고 LNG-FPSO의 연성된 6-자유도 운동응답을 계산하였다. LNG-FPSO의 정확한 Roll 운동을 추정하기 위해 점성효과는 Himeno(1981)가 제안한 경험식을 사용하였다.

Moonpool의 크기에 따른 운동감소의 경향을 파악하기 위해 이론적 계산과 실험적 방법으로 수행하였다. Moonpool 크기와 bilge step의 효과를 최적화 하기 위해 총 9가지의 case를 설정하였다. 이론 및 실험 결과로부터 본 LNG-FPSO는 moonpool과 bilge step의 장착으로 인한 감쇠력의 증가로 운동성능이 우수하다. 본 LNG-FPSO의 운동 응답중, 특별히 roll 운동이 다른 drillship, shuttle tanker등의 선박과 비교하여 상당히 작았고 이는 moonpool과 bilge step의 장착으로 인한 효과로 판단된다.

Cargo tank와 operation tank 크기를 검토 하기 위해 불규칙 해상중 sloshing 해석을 chamfer를 갖는 LNG-FPSO의 No.2, No.5 tank 벽면의 압력 분포와 자유표면의 time history에 초점을 맞추어 수행하였다. 최종적으로 tank 크기를 최적화 하였고 최적화된 tank는 선수사파와 횡파상태의 모든 filling에서 공진 현상과 충격 압력이 발생하지 않음을 확인하였다.

1. Introduction

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

Samsung Heavy Industries(SHI) has had much interest in it and made concept design for the new FPSO hull shape which is focused on the deduction 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, it is caused from the moonpool and bilge step in the hull body.

So 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 side of bilge as in a underlay of shoe. The ship has 161KT cargo capacity, one set azimuth thruster and 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 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 required process for the check of hydrodynamic loads on the tank wall. Paik and Ha (1998) analysed the sloshing phenomena for the cargo tank of 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 VOF(volume of fluid) algorithm which can express well the nonlinear motion of fluid.

2. Concept Design of 161KT LNG-FPSO

Basic scheme of the LNG-FPSO is based on the 138KT LNG carrier which is operated by Korea Gas Company.

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Topside of process plant on deck is assumed to be supplied by owner and is not included in this general arrangement. However the light weight of the topside is estimated about 17,000MT from 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 side of two moonpools and 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, specially roll, the adoption of bilge step and moonpool are considered. The effects of moonpool size and bilge step on ship motion is 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 practically existent by the moonpool size variation but is ignored in this research because of its small quantity. Finally the draught of ship for all the cases of calculation and experiment are fixed for the consistent comparison of motion performance.

3. Motion Calculation and Experiment

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, and so attributes all damping effects to wave making damping. This gives adequate results except roll motion for the most of oscillation modes of monohull ships, so viscous effect must be considered as for rolling. The viscous effects on the roll damping can generally be divided into four parts, like 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 some more for the half of the surface gives 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 as like Navis drillship with step as shown on Fig. 2, Table 2 and Fig. 3 which shows the dimension variations of moonpool in designed ship. The standard one

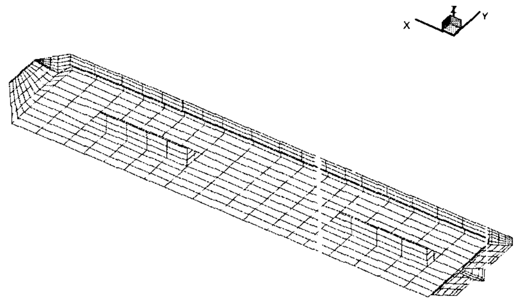

Fig. 1 Panel arrangement of FPSO

Fig. 2 The shapes of midship section

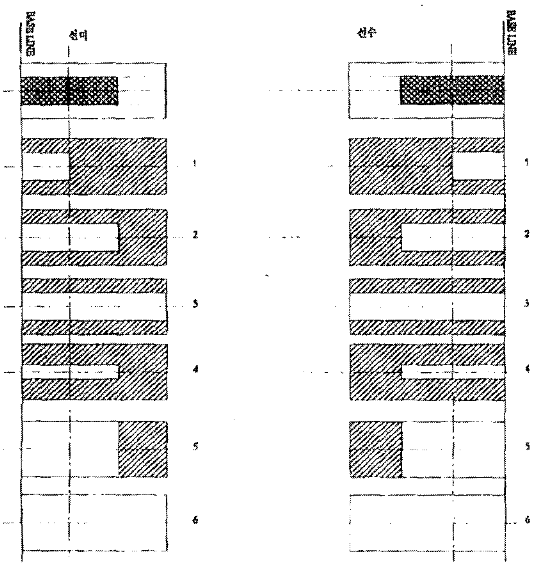

Fig. 3 The various moonpool types of FPSO

of designed LNG-FPSO is moonpool 2. 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 designed LNG-FPSO is significantly lower than general ship due to moonpool and bilge step effect.

For the analysis of the tank dimension propriety the roll and pitch motion trends are focused in this paper. Figs. 4 and 5 show the roll and pitch RAOs vs wave frequency of the FPSO for all cases in the Table 2 at zero forward speed. In the high frequency range consequently the roll and pitch motions approach to zero. In the case of the ship with bilge step and without moonpool as like Navis drillship, 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 as like general FPSO, the roll motion is 0.9deg/m which is slightly higher than previous case. Roll motion of designed LNG-FPSO is much low at zero forward speed compared to other ocean going ship vs wave frequency with moonpool1 at zero speed. The roll RAO has the peak value about 0.58 deg/m and 20.0second of period and is significantly reduced than without moonpool case. The effect of length and beam of moonpool is investigated in the cases of moonpool 1 to 6.

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

Figs. 6 and 7 are the results of model test for the roll and pitch motion. Model tests are carried out in the towing tank at Pusan National University with 2m model. These measured results show similar trend of the calculated one.

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

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

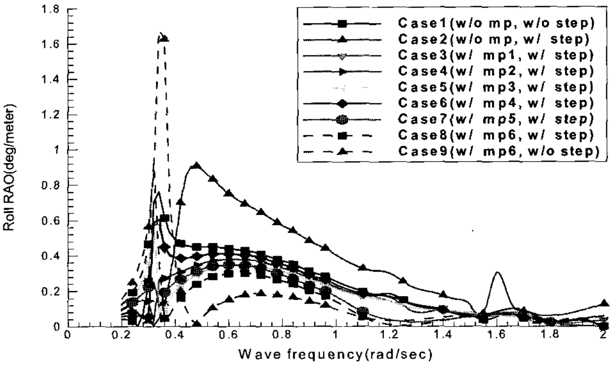

Fig. 4 Roll motion RAO in Beam seas (Cal.)

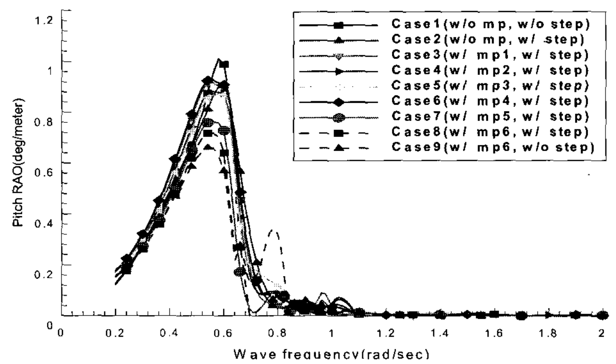

Fig. 5 Pitch motion RAO in Bow seas (Cal.)

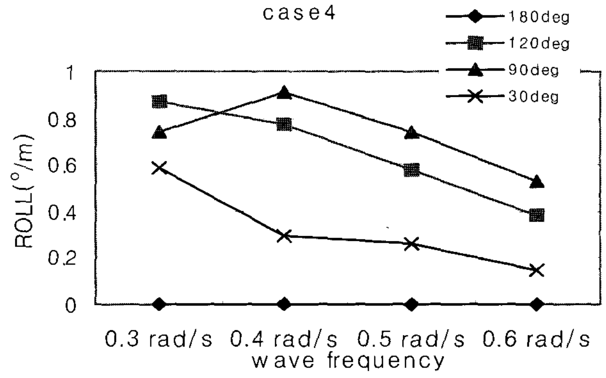

Fig. 6 Roll RAO (Experiment)

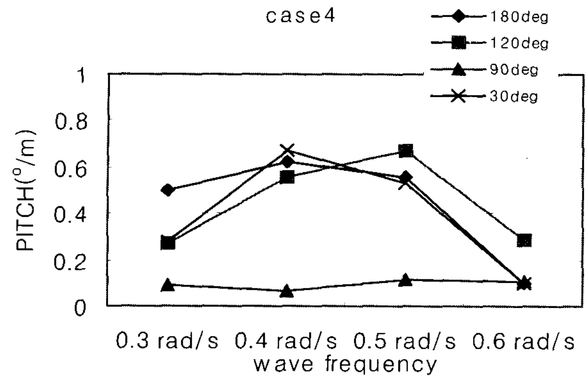

Fig. 7 Pitch RAO (Experiment)

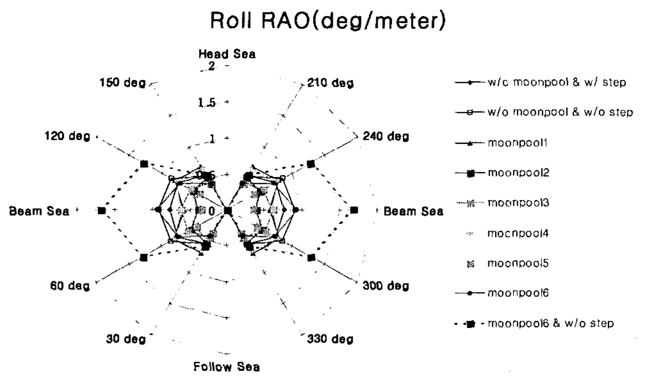

Fig. 8 Roll maximum amplitudes (Cal.)

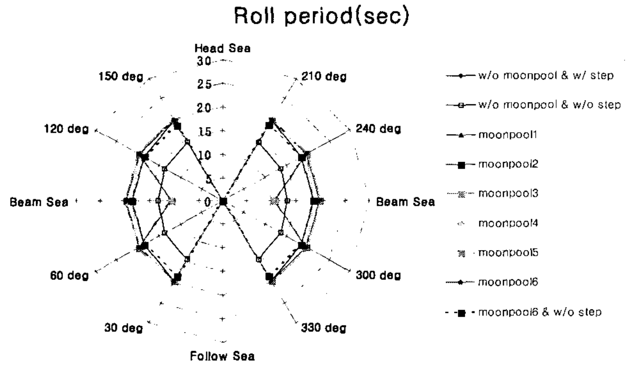

Fig. 9 Roll maximum periods (Cal.)

deg except moonpool 6 and without step. Due to moonpool effects, the roll period are shifted at beam seas. Fig. 10 shows the maximum pitch RAO and period classified by heading angles. All of the pitch RAOs of LNG-FPSO are under 1.0 deg/m except the case of without moonpool and with step. Unlike maximum roll periods, maximum pitch periods are not shifted at any heading angles.

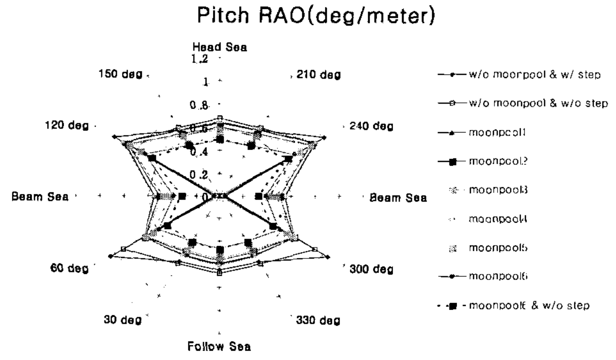

Fig. 10 Pitch maximum amplitudes (Cal.)

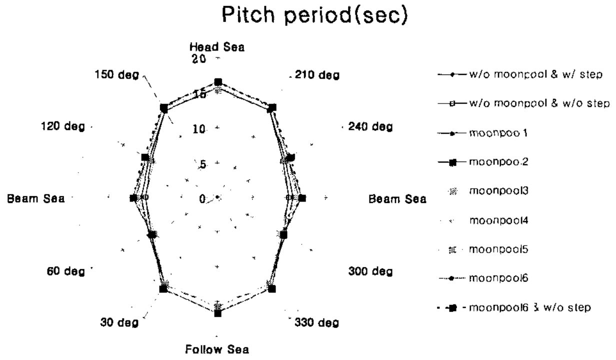

Fig. 11 Pitch maximum periods (Cal.)

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, liquid level and etc. The relation between the period of ship motion and the natural period of liquid motion in LNG tank greatly effect the sloshing load on the LNG tank wall. The sloshing analysis becomes very important procedure for the design of 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 No. 2 cargo tank and No. 5 cargo tank for the sloshing analysis because No. 5 tank has the longest distance between cargo tank center and the LCG of ship, and the dimension of No. 2 cargo tank is much larger than No. 1/No. 5 cargo tanks. Only port side tank of No. 5 cargo tank is also chosen because of the symmetric geometry of No. 5 tank. In this case, we investigate the sloshing effect for the port side tank of No. 5 cargo tank and No. 2 cargo tank.

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 3-dimension. The code can solve the Navier-Stokes equations and use VOF(Volume of Fluid) algorithm which can express well the nonlinear motion of fluid.

To investigate the sloshing effect in 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 No. 2 and No. 5 tanks. The second is sloshing simulation and impact pressure in the irregular motion/waves as the filling ratio of tank. Table 3 shows the principal dimensions of No. 2 and No. 5 tank.

Natural period of pitch motion can be estimated using 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 ship's natural period(10% fill departure condition) and tank's natural period is within 3 seconds(LR's rule). Thus it is expected that the resonance may occur in all fillings of No. 2/No. 5 LNG tanks, as shown in the Table 4. It is required to analyze sloshing effects for all fillings of 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) 11.89(10% loading)		12.19(s) 8.09(b)	LR

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 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 period are shown in Table 4. The difference between ship's natural period(10% fill departure condition) and tank's natural period have to be smaller than 5 seconds(LR's rule). Thus, in 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 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)

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

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 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 $H(\omega_e,\theta)$.

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

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

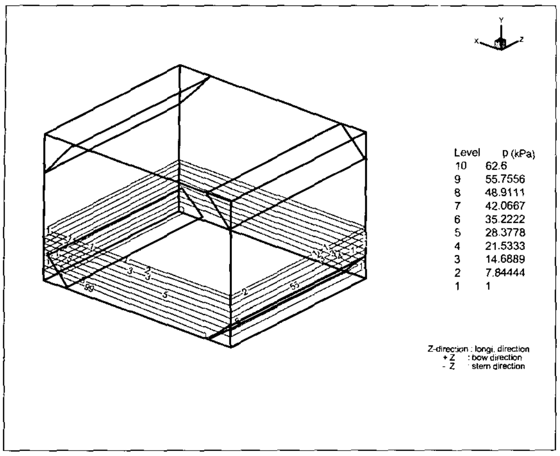

Fig. 12 Max. pressure of No.2 tank in 40% filling(beam)

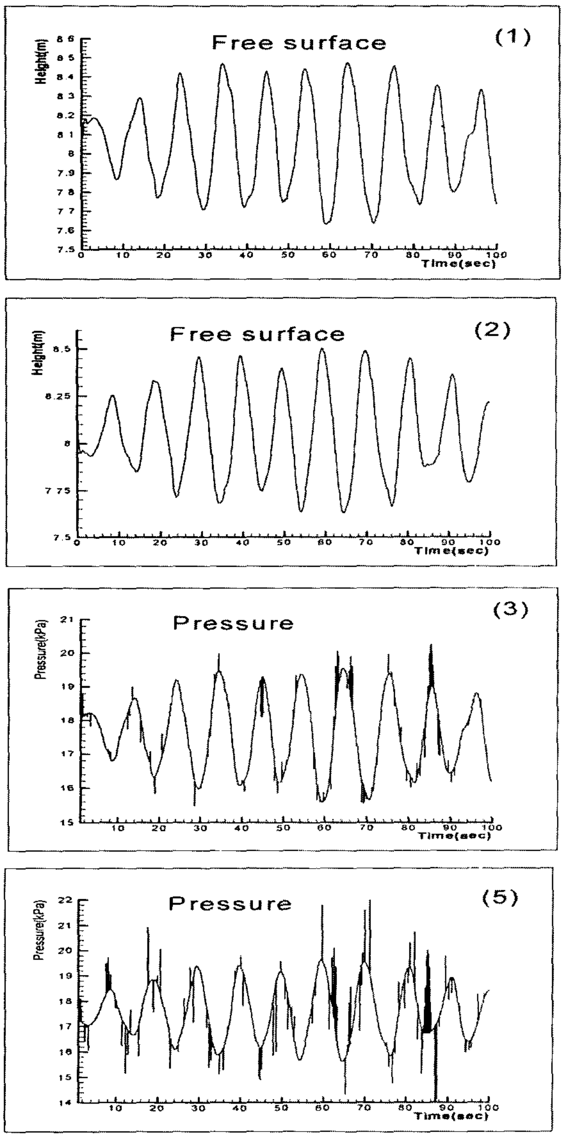

Fig. 13 Time history of No.2 tank in 40% filling(beam)

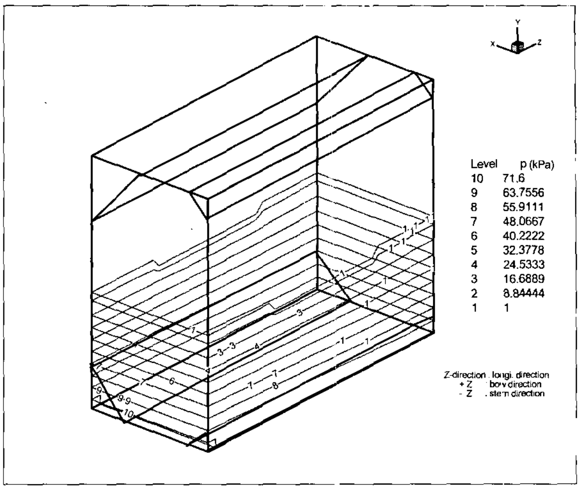

Fig. 14 Max. pressure of No.5 tank in 40% filling(bow)

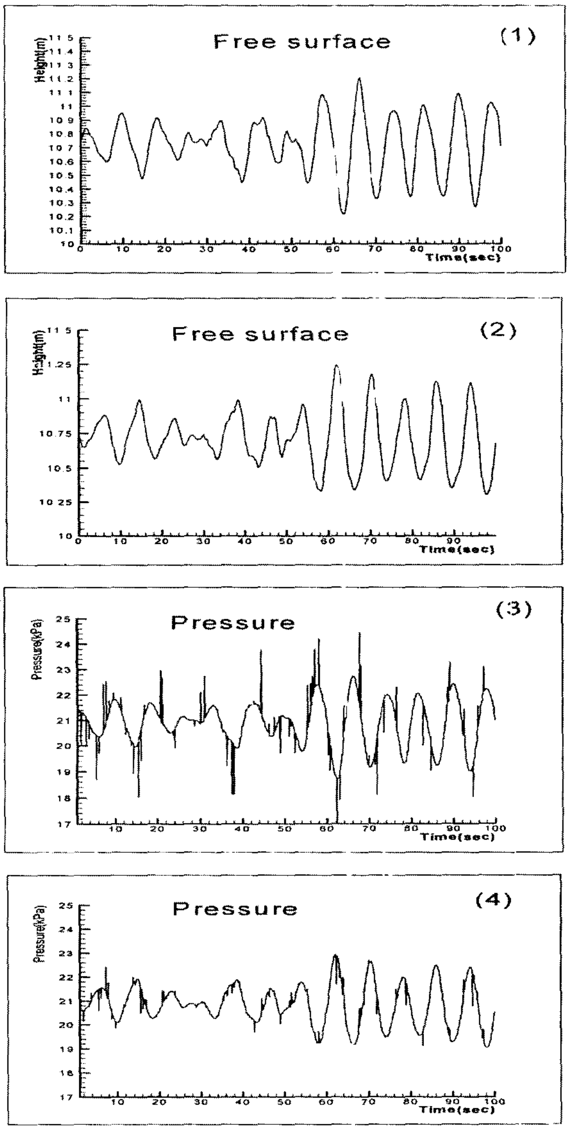

Fig. 15 Time history of No.5 tank in 40% filling(bow)

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 sea were considered for the sloshing analysis of No. 5 cargo tank because pitch RAO in bow quartering(120 deg.) is the largest. Roll motions in beam sea were considered for sloshing analysis of No. 2 cargo tank because roll RAO in beam sea(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 show the maximum pressure on the wall and Figs. 13, 15 show free surface and pressure detect positions of No. 2 and No. 5 cargo tank model. The sloshing analysis has been performed for No. 5 and No. 2 cargo tank 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 characteristic 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. For reducing the roll motion of the FPSO, the adoption of bilge step is very useful. But the effect of the moonpool is concluded to be not so comparatively large from the many cases which have been studied.

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 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 No. 2, No. 5 cargo tank of LNG-FPSO with chamfers. From these sloshing studies, we can infer that as follow;

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

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