한국해양공학회 2000년도 추계학술대회 논문집 PP. 189~195

Motion and sloshing analysis for new concept of offshore storage unit

by

Mun-Keun Ha, Mun-Sung Kim, Bu-Keun Paik, Chung-Hum Park
Hydrodynamics research, Samsung Heavy Industries Co., Ltd.
530, Jangpyung-Ri, Sinhyun-Up, Koje-city, Korea, 656-710
E-mail; mkha@samsung.co.kr, Tel.; +82-55-630-4742, Fax.; +82-55-630-4985

Abstract

New concept of LNG-FPSO ship with moonpool and bilge step in bottom is considered and investigated in the point of motion reduction and sloshing phenomena of the cargo and operation tanks. The cargo capacity of the ship of which principle dimensions is L x B x D x t(design) = 270.0 x 51.0 x 32.32 x 13.7(m) 161K at 98% loading condition. The two moonpools and rectangular step at bilge part are setted up specially for getting the effect of motion decrease.

For the motion analysis, linearized three dimensional diffraction theory with the simplified boundary conditions is used. The six-degree of freedom coupled motion responses are calculated for the LNG-FPSO ship. Viscous effects on the roll motion responses of a vessel are taken into account in this calculation program using an empirical formula suggested by Ikeda, Himeno and Tanaka[1] is used.

The case study for the moonpool size had been carried out by theoretical estimation and experimental method. For the optimization of the moonpool size and effect of the step, 9 cases of its size and with and without step are considered. From the results of calculation and experiment, it can be concluded that this designed LNG-FPSO ship have possibility to carry out her missions in the rough sea as for the owner's demand waves condition. The motion responses, especially roll motion, for the designed LNG-FPSO ship are much lower than those of another drillship and shuttle tanker and limit criterions are satisfied.

For the check of the cargo tank and operation tank sizes we have performed 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 No.5 tanks of LNG-FPSO with chamfers. Finally we got the tank size which has no resonance and no impact pressure in all filling in the bow quartering and beam sea.

1. Introduction

Currently many governments in the world have emphasized Liquefied Natural Gas(LNG) as a clean energy and concerned the gas development. Much of the natural gas is flared in the oil and gas field despite the economical and environmental loss. Many oil majors have a concern on the collection of gas and development of gas field. The LNG-FPSO development between oil major and consulting company has been discussed from 1990s but has ever come true.

Samsung H.I. has had much interest on 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 convinced that the ship has an distinguished motion performance. It is caused from the moonpool and foot step in the hull body. So the concept design of LNG-FPSO is also focused on the adoption of those system. The moonpools are located in the aft and fore body along to the centerline. This ship also adopted steps on both side of bilge as like a underlay of shoe. The ship has 161KT Cargo capacity, 1set 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 & Ikeda[2] studied the effects of viscosity on forces and motion response of offshore structures and floating bodies. The conceptually designed ship with moonpool and step is investigated theoretically and experimentally for the analysis of motion.

In the design of LNG related ship, sloshing analysis in the cargo tank is required process for the check of hydrodynamic load on the tank wall.

Paik & Ha[3] analysised 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 equation and uses VOF(volume of fluid) algorithm which can express well the nonlinear motion of fluid.

2. Concept design of 161K LNG-FPSO

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

To decrease the ship motion RAOs, the adoption of bilge step and moonpool are considered. The effects of moonpool size and bilge step on ship motion is investigated as shown 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 the all cases of calculration and experiment are fixed for the consistent comparison of motion performance.

3. Motion calculation and experiment

The motion analysis program is developed through the co-work between prof. Chun and SHI.[4] Linearized three dimensional diffraction theory with simplified boundary conditions is used. Ship motion calculation program is based on the panel method and is applicable to mono and/or twin hull vessels with and without forward speed. The detail of theoretical formulation and validation of the program refer to the published paper[4]. 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, those are skin friction, eddy making, hull lifting and bilge-keel damping components. In these calculations, all of those 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 discritized 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 show the dimension variations of moonpool in designed ship. The standard one 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 effect and bilge step.

For the analysis of the tank dimension propriety the roll and pitch motion trends are forcused 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 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 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($\beta = 150^{\circ}$). 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 Pusan national university with 2m model. These measured results show similar trend of the calculated one.

Figs. 8,9,10,11 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 max. value which classified by heading angles at upper part of these figures, all of the roll RAOs of LNG-FPSO are under 1.0 deg except moonpool6 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.

4. Sloshing Analysis

Sloshing impact load is the important external force to be considered in 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 affect to the sloshing load on the LNG tank wall. The sloshing analysis becomes very important procedure for the design of LNG tank because the damage due to severe sloshing loads on LNG tank walls 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 these reason, 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 estimated using the Eq.(4.1). The liquid motion period in the longitudinal direction is governed by the longitudinal shape of tank.

$$T = \sqrt{\frac{4\pi L}{g \cdot \tanh(h\pi/L)}} \tag{4.1}$$

The difference between ship natural period(10% fill departure condition) and tank 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.

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.

$$T = \sqrt{\frac{4\pi B}{g \cdot \tanh(h\pi/B)}} \tag{4.2}$$

The calculated natural period are shown in Table 4. The difference between ship natural period(10% fill departure condition) and tank 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 report 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.(4.3)

$$S(\omega_w) = \frac{173.0 H_{1/3}^2 / T_1^4}{\omega_w^5} \mathrm{EXP}\left(\frac{-691.0/T_1^4}{\omega_w^4}\right) \tag{4.3}$$

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 formulation;

$$S(\omega_e) = s(\omega_w) \frac{1}{1-(2\omega_w V/g)\cos\mu} \tag{4.4}$$

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(ωe, θ).

$$S_\phi(\omega_e,\theta) = S(\omega_e) \cdot G(\theta) |H(\omega_e,\theta)|^2 \tag{4.5}$$

Eq.(4.5) is a frequency domain function and can be transformed to a function of time. G(θ) is the directional wave spreading function. The time history of the ship motion in 6-DOF can be estimated from the following Eq.;

$$\eta_j(t) = \lim_{n \to \infty} \sum_{i=1}^{n} \cos\{\omega_i t + \varepsilon(\omega_i)\} \sqrt{S_j(\omega_i,\theta)\delta\omega} \tag{4.6}$$

j=1,2,3,4,5,6 ; surge, sway, heave, roll, pitch, yaw
These time history data of motions are used as the input data for the sloshing simulation of LNG-FPSO in the irregular waves.

The calculation conditions were that H1/3=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(120degree) is the largest. Roll motions in beam sea were considered for sloshing analysis of No.2 cargo tank because roll RAO in beam sea(90degree) is the largest.

We produced time histories of motions by using wave spectrums eqs. (4.3)(4.4)(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 6. There are no impact pressures and the the pressure value is abtout 0.2~1.5bars in all cases of filling.

5. Discussion and conclusions

A feasibility study of LNG-FPSO which is conceptually designed by Samsung is carried out. The investigation is focused on the motion characteristic and sloshing viewpoint. The motion estimation of the designed ship are theoretically carried out according to the with and/or without bilge step and various moonpool. For reducing roll RAO for the FPSO, the adpotion of bilge step is very useful. But the effect of the moonpool is concluded to be not so comparatively large from the many cases study.

For the check resonance between the ship motion and the fluid motion in cargo and operating tanks, we confirmed that there are 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, followings are concluded;

(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.

[REFERENCES]

[1] Ikeda, Y., Himeno, Y. and Tanaka, N., *"Component of Rolling damping of a ship at Forward speed"* Journal of the Society Naval Architects of Japan, 143, 1978, pp. 113-125

[2] John R. Chaplin, Y. Ikeda, *"Viscous Force on Offshore Structures and Their Effects on the Motion of Floating Bodies"*, Proc. 9th IOPEC, ISOPE, France, 1999

[3] P.K.Paik, M.K.Ha, M.S.Kim, S.Y.Kang,*"A Study on the Sloshing Phenomena of Membrane Type LNG Carrier in the Time Domain"*, Journal of the Society of Naval Architects of Japan, Vol.184, pp413-422, 1998

[4] M. S. Kim, H. H. Chun, Y. R. Joo,*"Design of a high speed coastal passenger catamaran with a superior seakeeping quality"*, Fast97, Sydney, 192-202

Table 1 Principal dimensions

particulars	dimensions
Length over all	278.00 m
Length between perp.	270.00 m
Breadth	51.00 m
Draft at design/scantling	13.7/14.5 m
Displacement at Td	162,140 m^3

Table 2 Cases of moonpool shape and step for cal.

	moonpool L x B = area (unit ; m)	step	remark
case 1	none	none	
case 2	none	O	
case 3	19.465 x 12.32 = 239.809(A/2)	O	m.p.1
case 4	38.930 x 12.30 = 479.618(A)	O	m.p.2
case 5	58.395 x 12.30 = 719.426(3A/2)	O	m.p.3
case 6	38.930 x 6.16 = 239.235(A/2)	O	m.p.4
case 7	38.930 x 24.64 = 959.235(2A)	O	m.p.5
case 8	58.395 x 24.64 =1438.853(3A)	O	m.p.6
case 9	58.395 x 24.64 =1438.853(3A)	none	m.p.6

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

Tank	Dimensions(unit m) (L x B x d)	Remarks
No.2	36.265 x 42.76 x 26.86	cargo
No.5(port)	36.265 x 14.92 x 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	
70	7.84	4.37	7.09	
80	7.70	4.37	6.99	
90	7.60	4.37	6.92	
Ship	27.35(scantling) 11.89(10%loading)		12.19(s) 8.09(b)	LR

Table 5 Maximum sloshing pressures of No. 2 and No. 4 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

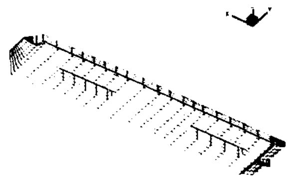

Fig. 1 Panel arrangement of FPSO

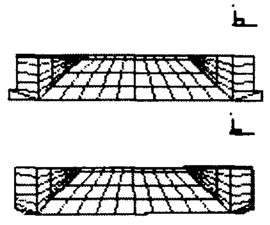

Fig. 2 The shapes of midship section

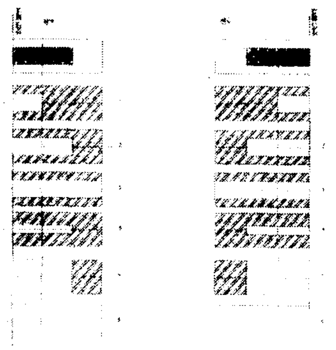

Fig. 3 The moonpool types of FPSO

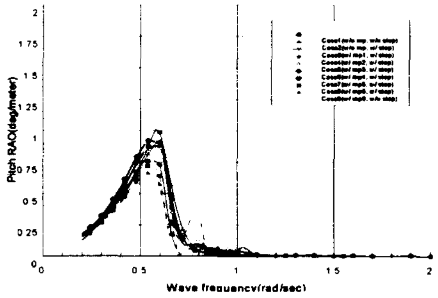

Fig. 4 Roll motion RAO in Beam seas

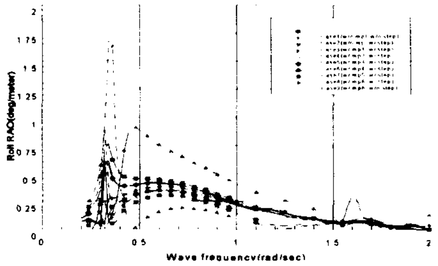

Fig. 5 Pitch motion RAO in Bow seas

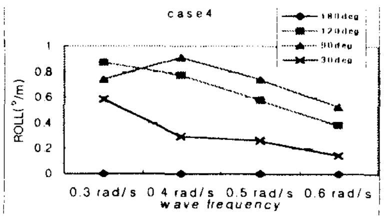

Fig. 6 Roll RAO (Experiment)

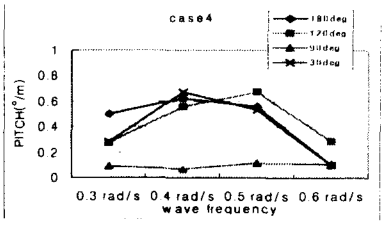

Fig. 7 Pitch RAO (Experiment)

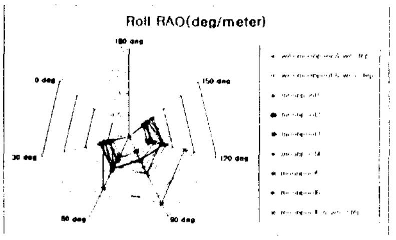

Fig. 8 Roll Maximum amplitudes(Cal.)

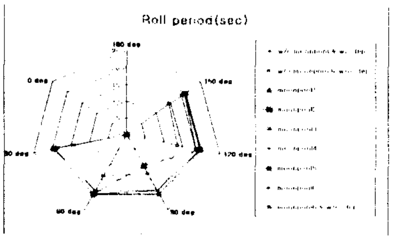

Fig. 9 Roll Maximum periods(Cal.)

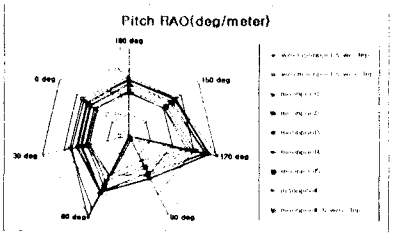

Fig. 10 Pitch Maximum amplitudes(Cal.)

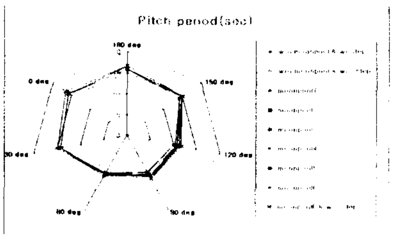

Fig. 11 Pitch Maximum periods(Cal.)

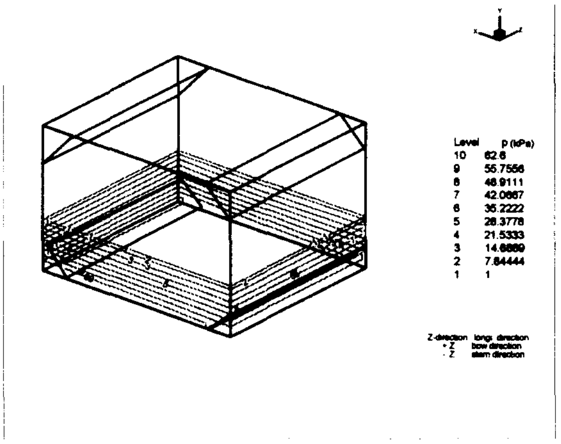

Fig. 12 Max. pressure of No.2 tank in 40% filling(beam)

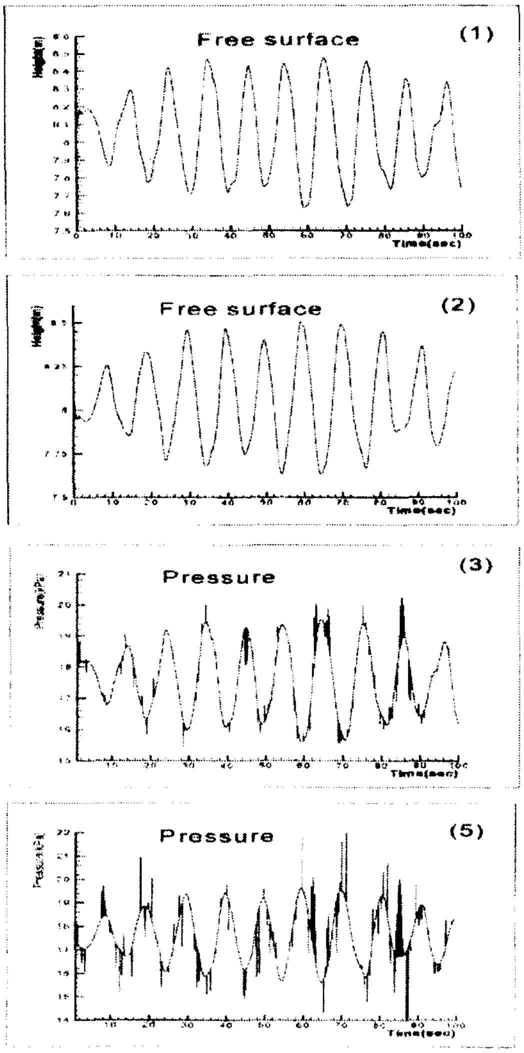

Fig. 13 Time history of No.2 tank in 40% filling(beam)

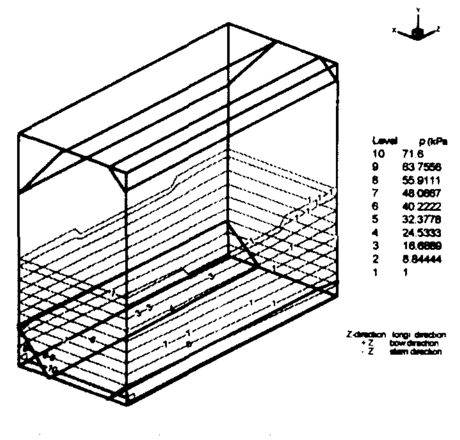

Fig. 14 Max. pressure of No.5 tank in 40% filling(bow)

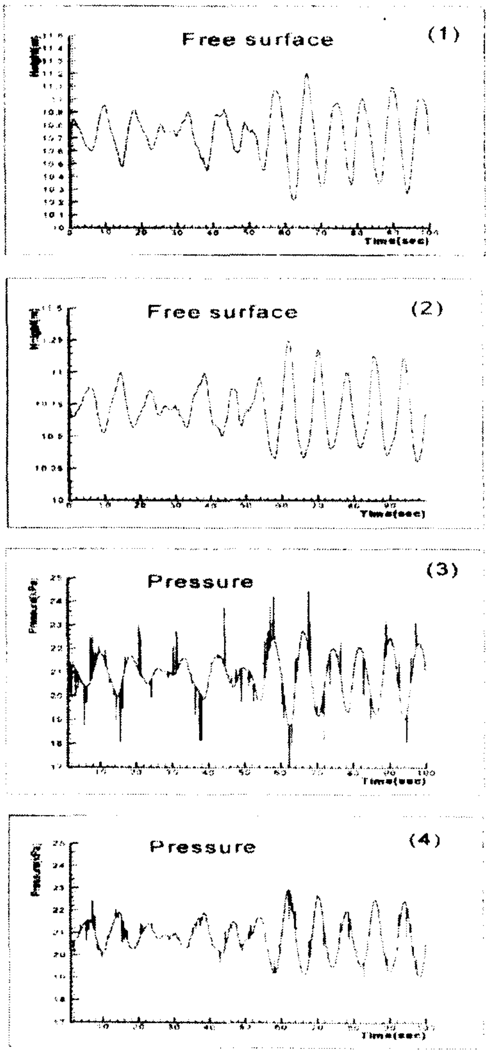

Fig. 15 Time history of No.5 tank in 40% filling(bow)