Investigation of Nonlinear Roll Motion Characteristics of a Shallow Draft Semi-submersible

Sa Young Hong[a), b)], Bo Woo Nam[a)], Nam Woo Kim[a)] and Yoon Sang Cho[b)]

a) Maritime and Ocean Engineering Research Institute, KIOST, Daejeon, Korea

b) Ship and Ocean Plant Engineering, University of Science and Technology, Daejeon, Korea

ABSTRACT

Steady roll motion of a semi-submersible with shallow draft is analyzed in regular waves. A 9-node higher-order boundary element method in frequency domain was adopted for numerical analysis of non-linear hydrodynamic force and motion characteristics of semi-submersibles. Artificial body surface damping was imposed to include viscous damping effects in scope of potential theory. A number of variations of pontoon shapes were considered to investigate major contributions to steady exciting roll moment. Some ideas on suppressing such nonlinear roll motions were discussed based on concept of minimizing nonlinear roll moments.

KEYWORDS

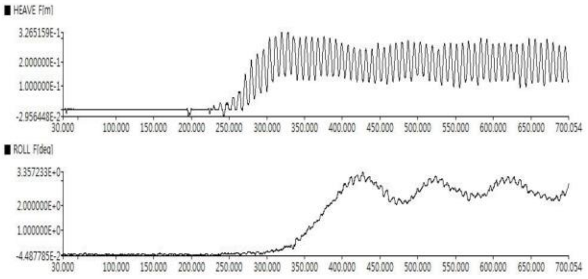
Nonlinear roll motion; Semi-submersible; Roll drift moment; Higher-order boundary element method; artificial body surface damping

INTRODUCTION

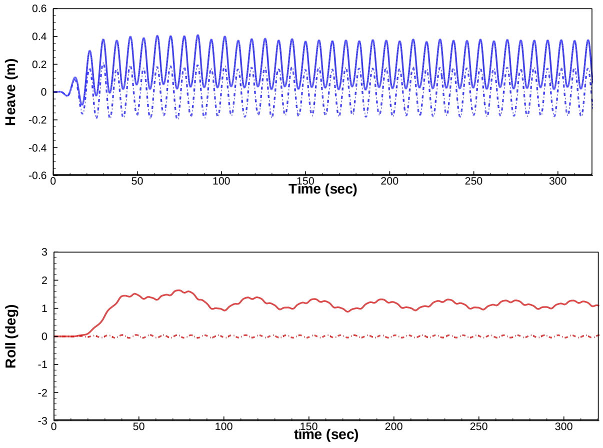
As oil and gas explorations have been expanding to deeper and deeper water regions, it is expected that use of semi-submersible platforms will be increasing due to its excellent global performance and flexibility as floating production platforms as well as deep water drilling rigs.

Main shape of the semi-submersible platforms is composed of submerged pontoons and vertical columns with small water-plane area which connect submerged pontoons and deck structure. Such typical features of the semi-submersible platforms make it possible to have small exciting forces and longer natural period of vertical mode motions. Further, the semi-submersible platform has less sensitivity to the direction of environmental loads due to winds, waves and currents than ship shaped FPSOs (Floating Production, Storage and Offloaing). Due to such favourable global performance which is essential for deepwater operations of floating platforms, there are now a few hundreds of semisubmersibles operating as mobile offshore drilling units and deepwater production platforms.

As the applied water depth becomes deeper and deeper, new concepts of semi-submersibles such as ones with deeper drafts and non-uniform pontoon shapes which were devised to meet higher standards of design requirements. One of deepwater semi-submersible design trend is to increase draft and add large damping plate to enhance vertical motion performance so that the use of dry tree can be a practical solution of deep water semi-submersibles. While, there have been another design trend which has shallow draft for deepwater drilling in relatively mild sea states. For this types of semi-submersible platforms there have been a few interesting findings called as list angle reported by Voogt et al. (2002, 2007). Voogt et al. (2002) firstly reported the phenomenon so called list angle which can be defined as occurrence of inclination (almost steady roll angle) under head sea condition. It was experimentally observed that the list angle occurs for specific wave periods and the existence of current magnifies the list angle. Because of almost steady heel angle under periodic wave actions, the second-order drift forces was suspected as one of major sources of the list angle.



(a) Model test



(b) FEM (dash line : 1st only , solid line : 1st + 2nd)

Fig. 1: Comparison of heave and roll motion in head waves, (H=2m, T=8 seconds, survival draft) (Hong et al., 2010)

Hong et al. (2010) also showed the same phenomenon by model test for a shallow draft semi-submersible platform. They numerically analysed the list angle both by frequency domain approach and time domain approach. In the frequency domain approach in which a numerically accurate higher-order boundary element method (Choi and Hong, 2002) was applied, it was found that vertical drift force noticeably increases for specific frequencies, which leads the draft to become shallower, and consequently corresponding roll drift moments also increase which results in list angle. It was an interesting finding that vertical heave drift force and roll drift moment has very close relationship. At those frequencies, roll drift moments increase rapidly for a small initial heel angle. This interpretation was verified by time domain FEM (Finite Element Method) approach (Hong and Nam, 2010). The time domain analysis results showed a good correlation with model test data with same condition (Fig. 1, Hong et al., 2010a).

The point to be mentioned on the list angle is that the list angle frequently occurred under shallower draft. There are two reasons for that, the one is that the roll drift moment increases noticeably as the draft becomes shallower, the other is that GM decreases as the draft becomes shallower which consequently induces list angle more easily.

In design and operational points of view, it is important to devise a hull form which is less susceptible to list angle phenomenon. In other words it is needed to design a hull which induces less roll drift moment in head sea condition to meet the design requirement.

Recently some remarkable novel concept offshore platforms were devised such as deep draft semi-submersibles which has large damping devices like truss spar does. For such shapes of platforms, it is necessary to ensure numerical convergence due to very thin plate structure with sharp edges and consideration of viscous damping effects as well. For this purpose a numerically efficient Higher-Order Boundary Element Method (HOBEM) was adopted developed by Hong et al. (2012). Hong et al. (2010b) showed that imposing artificial damping on body boundary condition gives identical effect on suppressing unrealistic resonant flow, so called gap resonance between side-by-side vessels. The artificial damping was introduced into the body boundary condition at the wetted surface in sloshing analysis in the frequency-domain by Zalar et al. (2007). Hong and Nam (2013) showed a number of numerical examples for various shape of floating bodies by using HOBEM in which artificial body surface damping was imposed, which demonstrated the usefulness of HOBEM combined with artificial body surface damping model for analysis of damping effects and treatment of complicated geometry structures.

In the present study, the effects of variations of hull form shapes of semi-submersible platforms are investigated to find a hull form less susceptible to list angle. Change of roll wave drift moment and trapping mode between main columns is analysed to find an effective way to reduce roll drift moment.

NUMERICAL ANALYSIS METHOD

Boundary Value Problem

In scope of potential flow model, the boundary value problem for analysis of floating body hydrodynamics can be constructed according to Green's second identity. The integral equation for the multiple-body hydrodynamics problem can be described as the following equation.

$$c(\vec{x})\phi(\vec{x}) + \sum_{j=1}^{NB}\int_{S_j}\phi(\vec{\xi})G_n(\vec{x},\vec{\xi})dS = \sum_{j=1}^{NB}\int_{S_j}\phi_n(\vec{\xi})G(\vec{x},\vec{\xi})dS \qquad (1),$$

ϕ, *G* and *c* represent velocity potential, wave Green function and solid angle, respectively. The subscript *n* denotes normal derivative, *NB* is the number of bodies. $\vec{x}$ and $\vec{\xi}$ represent field point and source point, respectively. The velocity potential satisfies Laplace equation as governing equation and boundary conditions on boundary surfaces such as body surface, free surface, bottom and radiation boundary surfaces.

- ***Laplace equation***

$$\nabla^2\phi = 0, \qquad \text{in fluid domain}\,, \quad (2)$$

- ***Bottom boundary condition***

$$\frac{\partial\phi}{\partial n} = 0, \qquad \text{on } z = \text{-}h\,, \qquad (3)$$

- ***Radiation condition***

$$\phi \to 0, \qquad \text{as } r \text{ tends to infinity}, \quad r = \sqrt{x^2 + y^2} \qquad (4)$$

In the present study only the body boundary surface condition is imposed by virtue of wave Green function.

- ***Body boundary condition***

$$\frac{\partial\phi_j}{\partial n} = -i\omega n_j, \qquad on \quad \sum_{k=1}^{NB} S_k, \quad (j = 1,...6\cdot NB) \quad , (5),$$

$$n_j = N_l, \qquad \text{for } \; j = 6(k-1) + l, (l = 1,...,6)$$

$$= 0, \qquad \text{for others.}$$

n_j and N_l denote directional cosines of *j*-th mode motion in global coordinate and *l*-th mode motion in body fixed coordinate. In the present study, the generalized mode approach is adopted so that this method can be easily expanded to handle multi-body hydrodynamics problem. The velocity potential is composed of potentials due to incident wave, radiation and diffraction waves.

$$\phi = A(\phi_I + \phi_S) + \sum_{j=1}^{6\times NB}\eta_j\phi_j \quad , \qquad (6)$$

Higher-Order Boundary Element Method

The basic idea of higher-order boundary element method is to introduce a higher-order interpolation function to describe behaviour of physical variables such as geometry, velocity potential, velocity and pressure. In the present study bi-quadratic 9-node element was employed. Details of HOBEM and generalized mode approach can be found in Choi and Hong (2002). Bi-quadratic approximation gives numerically accurate results with less number of elements compared with constant panel method, which is especially excellent for multi-body hydrodynamics and second order wave drift forces (Hong et al., 2005).

Artificial Damping Model

Implementation of body surface damping was made to add artificial damping term on the body surface boundary condition.

$$\phi_n = V_n + i\varepsilon k\phi\,, \tag{7}$$

V_n, ε and k are normal velocity on the body surface, arbitrary damping parameter and wave number, respectively. This model is a kind of numerical trick to include additional damping in scope of potential flow model but its effect is very similar to damping due to Morison equation (Hong and Nam, 2013). The additional damping slightly changes the kernel matrix, which gives viscous drag like damping.

NUMERICAL ANALAYSIS

Hull Form Variation

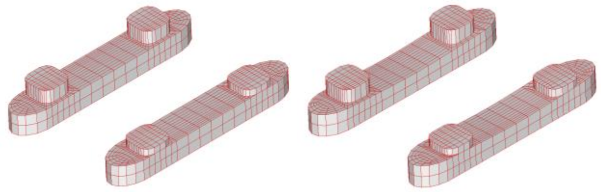
It was found that the roll drift moment which causes list angle is mainly induced by velocity square term contribution (Hong et al., 2010a). They also showed that the frequencies where list angle occurs have close relationship with frequencies at which trapping flow between main columns appears. The trapping flow can be interpreted as a kind of harbour resonance due to extremely shallow draft which has analogy with harbour and quay wall. There are three basic ideas considered for variation of hull form, with aiming at mitigation of roll drift moment under head sea condition with small initial heeling angle.

(1) Change of pontoon shape to mitigate trapping flow: non-uniform pontoon section, change of section aspect ratio

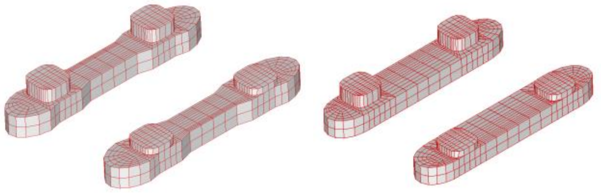
(2) Add of vertical barriers to block or shift resonance frequency

(3) Add of viscous damping device to dissipate kinetic energy of trapped water flow

Fig. 2 shows examples of group (1) & (2) hull shape variations. The basic hull form is the same model investigated by Hong et al. (2010a), the pontoon section shapes were changed in longitudinal direction but the displacement was kept constant. The distance between column centerline is 56m, the outer beam is 73m, draft is 14.5m and the displacement is 36,000 tons and GM is 1.56m.



(a) basic hull (b) pontoon local height



(c) pontoon local width (d) section aspect ratio

Fig. 2: Variations of pontoon shape of semi-submersible platforms

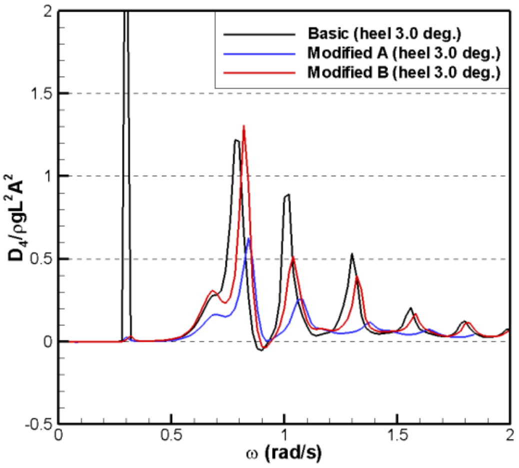


Fig. 3: Roll drift moment on semi-submersibles with different pontoon shapes

Fig. 3 shows non-dimensional wave drift force for three hull shapes. Drift force was calculated by so called near-field method (Pinkster, 1982). ‘Basic’, ‘Modified A’, and ‘Modified B’ in Fig. 3 correspond to (a), (b) and (c) in Fig. 2. The initial heel angle was set to be 3 degrees for all cases. It can be seen that the ‘Modified A’ shows noticeable reduction of roll drift moment which means that this type hull can be a candidate for reducing list angle in waves. But the ‘Modified B’ does not show noticeable reduction at the first peak while second and third peaks show some reductions. Since the occurrence frequencies of higher mode peaks are higher than the first peak frequency, corresponding drift forces will be negligible in real wave condition due to small wave height. Interestingly the ‘Modified B’ hull type is recently recognized for deep water semi-submersible due to its enhanced heave and roll performance compared with uniform section pontoon designs. Since the section variation of the ‘Modified A’ gives better performance than the ‘Modified B’, it is worthy to investigate roll drift moment reduction performance when the ‘Modified A’ has larger section variation.

Fig. 4 shows redesigned ‘Modified A’ models. The pontoon has the shape of thinner midship and thicker stem and stern. The heights of midship were reduced by 15% and 30 % than basic hull and heights of stem and stern increased to keep the displacement constant. The hull form named as ‘Modified D-1’ and ‘Modified D-2) as shown in Fig. 4.

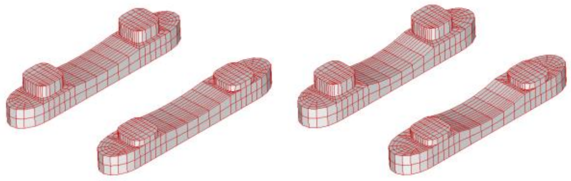


Fig. 4: Variations of pontoon shape of semi-submersible platforms (from left: Modified D-1 & Modified D-2)

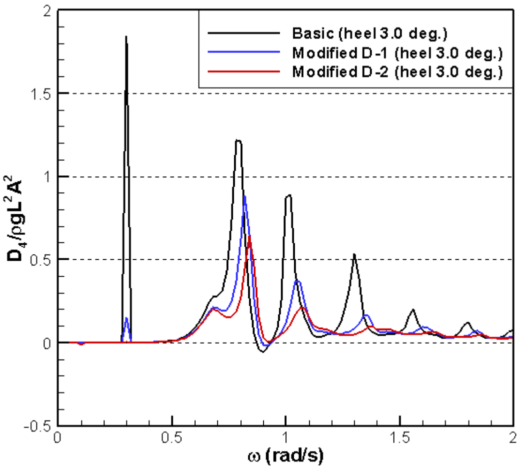
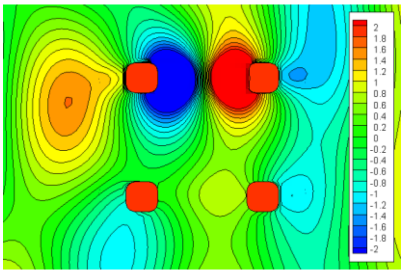


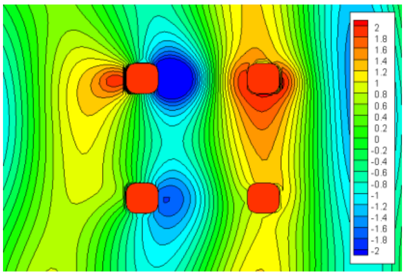
Fig. 5: Roll drift moment on semi-submersibles with different pontoon height variation

It can be clearly seen that larger variation of the section height along the pontoon length gives also noticeable reduction of roll drift moment. Remarkable reduction of roll drift moment was obtained by design change of pontoon section variations mainly by non-uniform pontoon height distributions. This result implies that the section variations of height along the pontoon mitigate so called trapping of flows between columns of semi-submersibles. Comparing to the ‘Modified A’ and ‘Modified D’, it can be also seen that the shape around main columns influences reduction of steady roll exciting moment. It was found that the sheared shape around the columns the ‘Modified A’ acted a positive role. The non-uniform section shape of pontoons seems to weaken resonance behavior of flows inside fluid domain surrounded by pontoons and columns which has a little bit non-structured shape than the case of uniform pontoons and columns.

Fig. 6 shows wave contour snap shots for trapped wave conditions. The contours for the ‘Basic hull’ and the ‘Modified A’ are compared. It can be seen that the ‘Modified A’ mitigated trapped wave patterns between columns, which reduced roll drift moment significantly.



(a) Basic hull



(b) Modified A

Fig. 6: Heave and Pitch responses of semi-submersibles for different pontoon variations

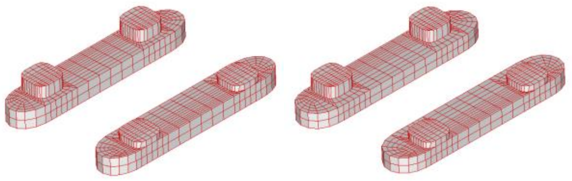


Fig. 7: Variations of pontoon height and width of semi-submersibles (from left: Modified C-1 & Modified C-2)

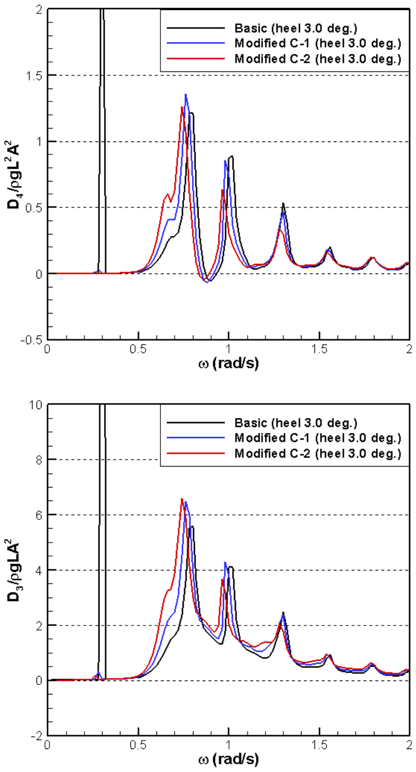


Fig. 8: Roll and heave drift moments on semi-submersibles with different pontoon height-widths ratio

Fig. 7 shows the case of pontoons with variation of height and width ratio. Pontoon height was reduced by 10% and 20% while width was increased in proportion to the change of height. In this case the fluid domain surrounded by pontoons and columns has a similar shape with the case of basic hull, it can be expected that the behavior of trapping water flows will be similar but the resonance frequency will be slightly shifted due to size change of the fluid domain. As shown in Fig. 8, the peaks of roll drift moment shifted to lower frequencies for first two modes. The magnitude of the peaks seems to be insensitive to the section changes. Corresponding heave drift forces show almost same behavior with the roll drift moments, which demonstrates close correlation between heave and roll drift forces. D_3 and D_4 represent heave drift force and roll drift moment, respectively.

Fig. 9 shows hull forms equipped with vertical barriers along the pontoon, of which target was to shift trapping flow modes.

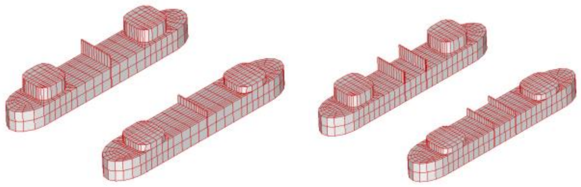


Fig. 9: Hull form variations by adding vertical barriers along the pontoon length (from left: Modified E-1 and E2)

It is interesting to find that adding vertical barriers magnified peaks of roll drift moments, which means that trapped wave flow behaviors cannot be suppressed by adding vertical barriers. It just shifted occurrence frequencies while amplitude of peaks was increased noticeably. The peak frequencies shifted to lower values significantly, adding vertical barrier may cause worse situation in view of suppressing occurrence of list angle because magnitude of roll drift moment will increase in real sea condition due to higher waves.

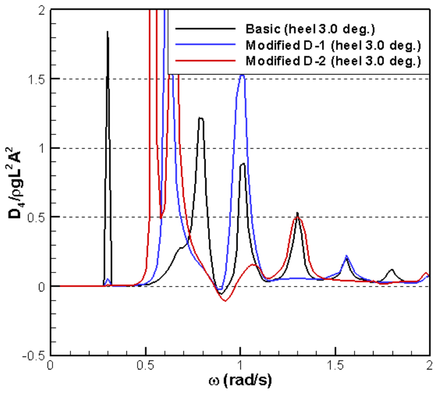


Fig. 10: Roll drift moment on semi-submersibles with vertical barriers along the pontoon

Finally the effect of adding appendages on the topside of pontoons was investigated. Adding appendages on the surface of pontoons induces viscous damping effect which dissipates kinetic energy due to trapping resonance flows. As shown in Fig 11, it can be seen that adding pontoon surface damping significantly reduced the magnitudes of roll drift moments as a consequence of reduction of trapped wave between main columns. The reduction rate is in proportion to damping parameter, which implies that addition of high viscous damping appendages on pontoon surface can suppress the list angle significantly.

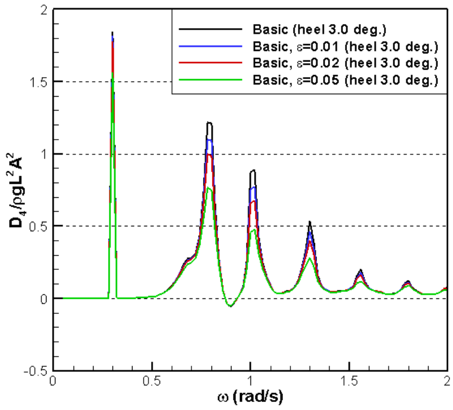


Fig. 11: Roll drift moment on semi-submersibles equipped with appendages on the topside of pontoons

Figs. 12 and 13 shows overall trend of surge drift moments and roll motion responses for hull for variations.

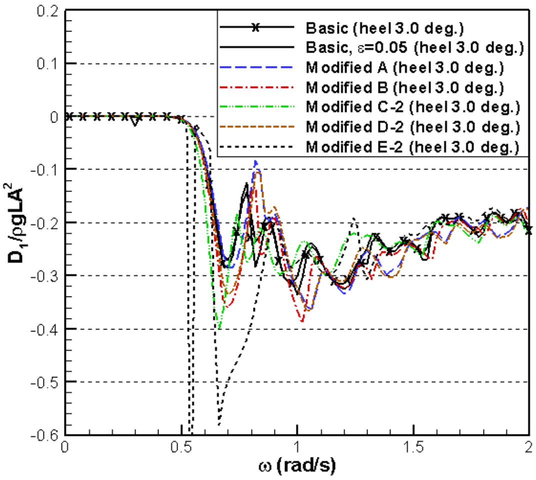


Fig. 12: Surge drift moments on semi-submersibles for various hull form variations

It was observed that most of hull form variations except add of viscous hull damping partially induced increase of longitudinal wave drift force which is a disadvantageous factor for mooring system design. The case of adding vertical barriers noticeably magnified surge drift force while the case of adding hull viscous damping gave little change in surge drift force. This is one of advantageous factors of design change by adding partial viscous damping on the topside of pontoons for suppressing occurrence of list angle.

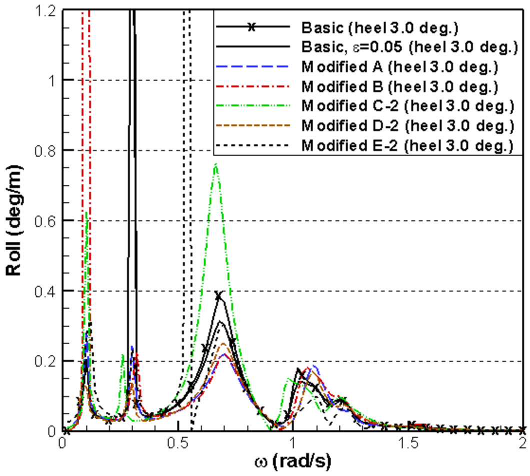


Fig. 13: Roll motion response in regular heave waves of semi-submersibles for various hull form variations

Wave frequency roll motion is mainly governed by GM as well as hull shapes. As shown in Fig. 13, most of hull form variations gave favorable effects on roll motion except the ‘Modified C & E’ which increased roll motion inside wave frequency ranges significantly presumably due to wide pontoon and vertical barriers which may increase roll exciting moment.

CONCLUSIONS

The effect of hull form variations of semi-submersible platforms was investigated on suppressing occurrence of list angle by numerical analysis of roll wave mean drift force. A higher-order boundary element method combined with artificial body surface damping was applied successfully by virtue of its numerical accuracy and consistent modelling of viscous damping in scope of potential flow analysis. Through a series of hull form variations and analysis of roll wave mean drift moment on the hulls, the following conclusions are drawn.

1) Suppressing occurrence of list angle is possible by either variation of pontoon hull which weaken trapped wave flows or adding strong viscous damping appendages which dissipates kinetic energy of trapped wave flows.
2) Non-uniform pontoon section variation is helpful to reduction of roll wave drift moment which is a main trigger of list angle occurrence in head waves.
3) The non-uniform variation of upper surface of pontoons gave a more efficient result than other hull form variations.
4) Adding viscous damping appendages on the upper surface of pontoons did not induce additional increase of surge drift force while other methods induced not negligible increase in surge drift force.

ACKNOWLEDMENTS

The present work was supported by the principal R&D program of MOERI/KIOST: “Performance Evaluation Technologies of Offshore Operability for Transport and Installation of Offshore Structures” granted by Korea Research Council of Public Science and Technology. This work was also partially supported by a Grant-in-Aid for Strategy Technology Development Programs from the Korea Ministry of Trade, Industry and Energy (No.10038598).

REFERENCES

Choi, YR and Hong SY (2002). “An Analysis of Hydrodynamic Interaction of Floating Multibody Using Higher-Order Boundary Element Method,” Proc 12th Int. Offshore and Polar Eng Conference, ISOPE, Kita-Kyushu, pp 303-308

Hong, SY, Nam BW and Cho SK (2012). “Analysis and interpretation of gap resonance phenomenon of side-by-side moored vessels,” Proc 2012 Ship Hydrodynamics Research Society Summer Conference, August 13, 2012, Seoul, SNAK

Hong, SY and Nam BW (2013) “Development of a HOBEM combined with artificial damping model,” Proc Offshore Plant Design Research Society 2013 Summer Conference, June, 20-21, 2013, Mokpo, KSOE

Hong, SY, Nam, BW, Kim, JH, Hong, SW, Kim, YS (2010a). “Secon-order motion characteristics of a semi-submersible platform in waves,” Proc 11th PRADS, pp. 266–274

Hong, SY , Nam, BW and Cho, SK(2010b), A Study on characteristics of wave mean drift forces acting on side-by-side moored vessels (in Korean), Proc. Annual Conference of the Korean Society of Ocean Engineers, Mokpo, Korea, 2010, pp. 199-206

Hong, SY and Nam BW (2010). “Analysis of Secondorder Wave Force on Floating Bodies Using FEM in Time-domain,” Proc 20th Int. Offshore and Polar Eng Conference, ISOPE, Beijing, pp. 372-378

Hong, SY, Kim, JH, Cho, SK, Choi, YR, Kim, YS (2005). “Numerical and experimental study on hydrodynamic interaction of side-by-side moored multiple vessels,” Ocean Engineering 32 pp 783–801

Pinkster, J.A. (1980). “Low frequency second order wave exciting forces on floating structures,” Netherlands Ship Model Basin, Publication No.650.

Voogt, AJ, Soles, JJ and Dijk, RV (2002). “Mean and Low Frequency Roll for Semi-submersibles in Waves”, Proc 12th Int. Offshore and Polar Eng Conference, ISOPE, Kita-Kyushu, pp. 379-384

Voogt, AJ and Soles, JJ (2007). “Stability of Deepwater Drilling Semi Submersibles,” Proc 10th Int Symp on Practical Design of Ships and Other Floating Structures, Houston

Zalar, M., Diebold, L., Baudin, E., Henry, J., and Chen, X.B.(2007). “Sloshing effects accounting for dynamic coupling between vessel and tank liquid motion,” Proc. 26th Int. Conference OMAE, San Diego, OMAE2007-29544