Ocean Systems Engineering, Vol. 2, No. 3 (2012) 217-228
DOI: http://dx.doi.org/10.12989/ose.2012.2.3.217

Hydrodynamic interactions and coupled dynamics between a container ship and multiple mobile harbors

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(Received June 30, 2012, Revised August 16, 2012, Accepted September 5, 2012)

Abstract. As the size of container ships continues to increase, not many existing harbors can host the super-container ship due to its increased draft and the corresponding dredging requires huge budget. In addition, the minimization of waiting and loading/offloading time is the most important factor in harbor competitiveness. In this regard, mobile-harbor concept has been developed in Korea to achieve much improved harbor capacity and efficiency. In developing the concept, one of the most important elements is the operability of crane between two or more floating bodies in side-by-side arrangement. The container ship is to be stationed through a hawser connection to an outside-harbor fixed-pile station with the depth allowing its large draft. The mobile harbors with smart cranes are berthed to the sides of its hull for loading/offloading containers and transportation. For successful operation, the relative motions between the two or more floating bodies with hawser/fender connections have to be within allowable range. Therefore, the reliable prediction of the relative motions of the multiple floating bodies with realistic mooring system is essential to find the best hull particulars, hawser/mooring/fender arrangement, and crane/docking-station design. Time-domain multi-hull-mooring coupled dynamic analysis program is used to assess the hydrodynamic interactions among the multiple floating bodies and the global performance of the system. Both collinear and non-collinear wind-wave-current environments are applied to the system. It is found that the non-collinear case can equally be functional in dynamics view compared to the collinear case but undesirable phenomena associated with vessel responses and hawser tensions can also happen at certain conditions, so more care needs to be taken.

Keywords: mobile harbor; fixed-pile station; side-by-side arrangement; hawser/fender; mooring lines; multiple floating bodies; relative motions; hull-mooring coupled dynamics; non-collinear wind; wave; current

1. Introduction

Existing harbors continue to have difficulty in hosting super-size container ships due to their ever-increasing capacity and draft. As an effective solution of this kind of problem, a mobile harbor, as a midway loader, was proposed. The concept is that the container ships are to be anchored in the near shore outside breakwater, and multiple mobile harbors with smart crane approach for docking in side-by-side arrangement. Then, the containers would be disembarked/embarked from the container ship to the loader and vice versa. Using the mobile harbor with shallow draft and high speed, the containers would be very effectively transferred to the harbor or inland cities along rivers. The lack

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of facilities/infrastructure or the depth limitation of existing harbors would be solved this way. For the effective and speedy operations such as docking, loading/offloading, and transferring, specially devised cranes and docking/mooring systems need to be developed.

In this study, the hydrodynamic and mooring analyses are performed for three floating vessels, a container ship and two mobile harbors on both sides of the ship in side-by-side arrangement, in the open sea. There are hawser lines and fenders between the three floating vessels. The container ship is supposed to be tied to a fixed-post parking station through two bow hawsers so that it can freely weathervane to minimize environmental loadings (Ma 2009).

The proper design of the system needs a reliable prediction of moored vessel responses and its dynamic coupling effects through hawser lines and fenders in operating environmental condition.

In this research, the hydrodynamic interactions of the three floating bodies, container ship and two mobile harbors, with various multiple elastic lines between them are solved by a time-domain multi-vessel-mooring coupled dynamic analysis program, HARP/CHARM3D, which has been developed by the corresponding author research group during the past decade (Ran 2000, Kim 2001, Tahar 2003, Kim 2005).

The coupled dynamics of two floating vessels in side-by-side arrangement have been studied by Buchner *et al*. (2001, 2004), Lee and Kim (2004), and Koo and Kim (2005). Koo and Kim (2005) introduced two different methods in hydrodynamically/elastically coupling two floating vessels in side-by-side arrangement. Choi and Hong (2002) and Kang *et al*. (2010) compared the numerical simulations of two vessels against respective experiments.

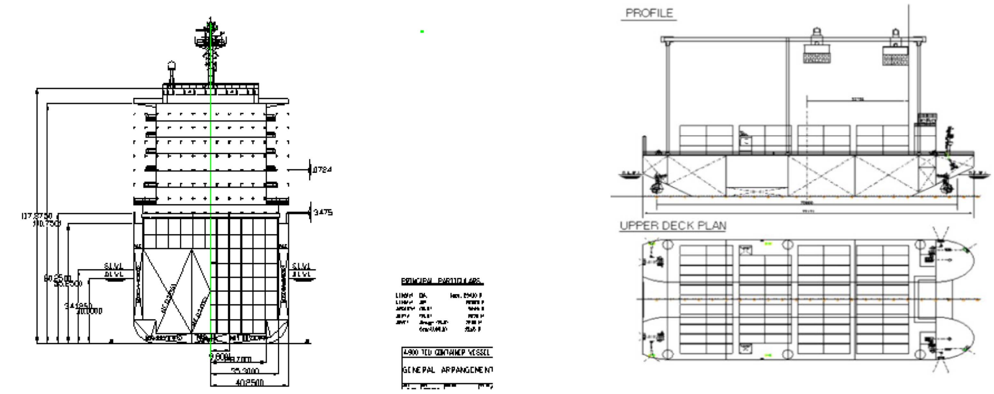
In the present study, we investigate the full hydrodynamic interactions of the three floating bodies, a typical 5000-TEU container ship and two catamaran-type mobile harbors on both sides, and their coupled dynamics with various types of multiple elastic lines. We particularly focus on the relative motions between the three vessels to check crane operability and the safety of mooring system in a typical wind-wave-current environment of sea-state 4. In particular, the behaviors of the whole system in the non-collinear environment are simulated and compared to those of collinear cases.

2. Description of the problem

2.1 The principal data of ships and environments

In this study, the subjected vessels include a 5,000-TEU container ship and two catamaran-type mobile harbors. For the selection of the vessels, the capacities, global performance, navigability/maneuverability, and the structural safety were considered. Figs. 1(a) and (b) show the profiles of the two ships, and their particulars are given in Table 1, as an initial design.

The operating condition of the mobile harbor is taken as the sea state 3 or less that could be encountered in the aimed sea area of 26 m water depth. In the present study, the relatively mild sea-state 4 is considered as the upper limit of the loading/offloading operation. The wind-wave-current condition of the sea state 4 is summarized in Table 2. Both collinear and non-collinear cases are considered. The uni-directional random waves are generated from a PM spectrum and the random wind velocities are generated from an API wind spectrum. Steady uniform current with given velocity is assumed. All the directions are given with respect to positive x axis. The origins of the body coordinate systems for the container ship and mobile harbor are located on the MWL (Mean Water Level) and 115 m and 46 m from stern, respectively.



(a) (b)

Fig. 1 (a) Forward view of container ship and (b) column/plan view of mobile harbor

Table 1. Initial particulars of container ship and mobile harbor

Item	STX container ship	Mobile harbor
Displacement (Ton)	75,797	7,469.3
LOA (m)	294.1	76.75
LBP (m)	283.0	70.0
Breadth (mld) (m)	32.2	33.0
Depth (mld) (m)	22.1	11.0
Draft (design) (m)	12	5.3
Cb	0.6763	0.5976
KG (m)	14.151	14.471
LCB (m) from stern	130.13	45.83
LCG(m) from stern	129.03	44.55
Kxx/*Kyy*/*Kzz*	12.88/67.92/67.92	13.2/16.8/16.8

Table 2. Environmental conditions

Environmental condition (SS4)	Collinear	Non-collinear
H_S(significant wave height) / T_P(peak period) / heading	1.6 m/10 sec/180 deg	1.6 m/10 sec/180 deg
Wind velocity (at 10 m)/ direction	9.8 m/s/180 deg	9.8 m/s/195 deg
Current velocity / direction	0.8 m/s/180 deg	0.8 m/s / 165deg

2.2 Numerical modeling

It is assumed that the container ship is parked at the fixed-pile station. There are two hawsers from the bow of the containership to the fixed pile, and the vessel is free to weathervane to minimize environmental loadings. The bow of the container ship is placed about 50 m away from the center of pile. The container ship and the two mobile harbors are in side-by-side arrangement, as

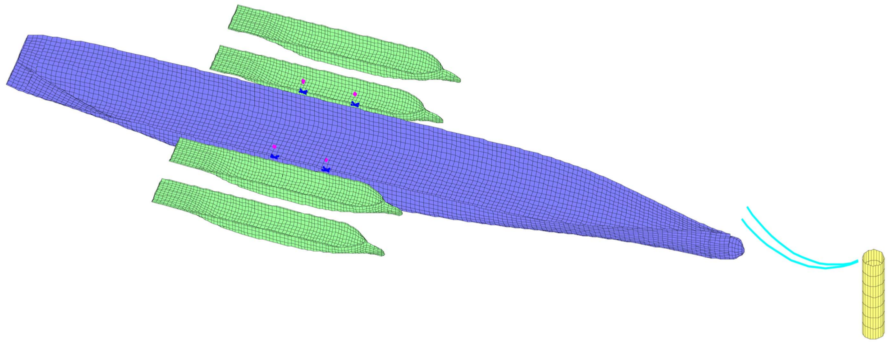


Fig. 2 Schematic view of the mobile harbor system and panels for hydrodynamic calculations

Table 3. Specification of hawser/fender system

	Bow hawsers	Side hawsers	Fenders
Axial Stiffness [N/m]	7.962E+7	7.962E+7	6.0E+6
Length [m]	50	3.5	1.5
Pretension [N]	1.40E+3	1.10E+2	•
Dry Weight [kg/m]	25	25	•

shown in Fig. 2, and there are two *X*-shaped hawser lines and fenders (marked by red blocks), between the vessels. The gap is 2 m and the fender height is 1.5 m. Each set of hawsers and fenders are placed at ±10 m from the center of *x* axis for the body coordinate system. Specifications of the hawsers and fenders are summarized in Table 3.

The hydrodynamic coefficients and wave forces on the three floating bodies are obtained from a 3D diffraction/radiation panel program WAMIT (Lee 1991). For paneling the submerged parts, 4559, and 2296 elements are used for the container ship and mobile harbor. To generate the slowly-varying horizontal-plane vessel motions, the second-order mean drift forces are calculated and included through the so-called Newman's approximation method, which is to be valid since the horizontal stiffness for horizontal-plane motions is very small. The exaggerated mean drift forces by the potential theory at the pumping mode inside the gaps are empirically adjusted (Buchner 2004, Kang *et al*. 2010).

The time-domain simulations of the three floating bodies with mooring lines are conducted by the multi-vessel-mooring coupled dynamic analysis program HARP/CHARM3D. The elastic lines are modeled by global-coordinate-based FE (finite element) method using higher-order rod elements. For each of the bow and side hawsers, 15 and 5 cubic elements are used. The three vessel motions are fully coupled in hydrodynamic interactions by the 18×18 matrices and they are combined with the additional line dynamics FE-DOFs (finite-element degree of freedoms) in a big combined matrix at each time step. In this research, the 3-body system is simulated for about 1,800 sec with time step = 0.0025 sec. Ramp function is applied for the first 10,000 steps to minimize the initial transient effects. Convergence is carefully checked with respect to hull panels, line elements, and time steps.

For the current coupled dynamic analysis, a proper modeling of hull viscous damping for the vessels is necessary to obtain more reliable motion results. In case of the container ship, 7 plates for sway, 1 plate for surge, and five truss members are used to capture the hull viscous damping. For the mobile harbor, considering twin hull shape, 1 surge and 8 sway plates with five truss members are applied for each hull.

3. Numerical simulation results

The two types of environmental conditions, collinear and non-collinear wind-wave-current, are applied to the system. In case of the non-collinear environment, undesirable mean roll angle occurs due to the asymmetry of environment, the relatively weak roll restoring moment, and the mean yaw angle with respect to the anchoring point associated with yaw-roll hydrostatic coupling effects. The roll-yaw coupling effects are given by $C(4,6) = -Bx_b + Wx_g$, in which B is buoyancy, W is weight, and x_b and x_g are longitudinal centers of buoyancy and gravity. Therefore, to reduce the undesirable mean roll angle, the container ship's KG and LCG are slightly adjusted, as shown in Table 4, and the revised case is re-run for the same non-collinear environment. In Table 4, C is hydrostatic coefficient, T is dry natural period, and 4 and 6 mean roll and yaw modes. It needs to be noted that the KG and LCG can vary depending on weight distribution and during the process of loading/unloading operation.

The 6DOF responses of the containership and the port- and starboard-side mobile harbors are plotted in Fig. 3 for the three different cases. In the figures, the collinear cases are blue (dashed) lines, and the non-collinear cases for old/new condition are light (solid)/dark (dash-dot) green lines.

In the collinear case, the mean yaw angle is close to zero due to geometrical symmetry and the corresponding 6DOF responses are within reasonable boundaries. Even in the collinear case, if only one MH is docked on one side, the geometric symmetry is not satisfied and the mean yaw angle is not necessarily close to zero. Slowly-varying surge motions are superposed with wave-frequency motions with respect to the mean position. Compared to the collinear case, the non-collinear case with the old KG and LCG values shows about 7 degree mean yaw angle due to the non-symmetric environmental loadings. The mean yaw angle also causes the corresponding mean sway and surge positions as a result of the geometric relations of the single-point-moored system. It is of interest to note that there is also a mean roll angle of about 4.5 degrees in the non-collinear case only for the container ship. From the point of crane operation, the weathervaning mean yaw angle does not cause any problem but the mean roll angle may cause trouble. The mean roll angle of the container ship is primarily caused by the unusually small roll restoring moment with the original KG value, which also results in unusually large roll natural period, as shown in Table 4. To make the matters

Table 4. Revision of particulars for container ship

Item	Initial(old)	Revised(new)
KG	14.151 m	12.751 m
LCG(from stern)	129.03 m	130.03 m
$C(4,4)$	3.959E+08 Nm/rad	1.434E+09 Nm/rad
$C(4,6)$	-8.255E+08 Nm/rad	-8.416E+07 Nm/rad
$T(4,4)$	37 sec	19 sec

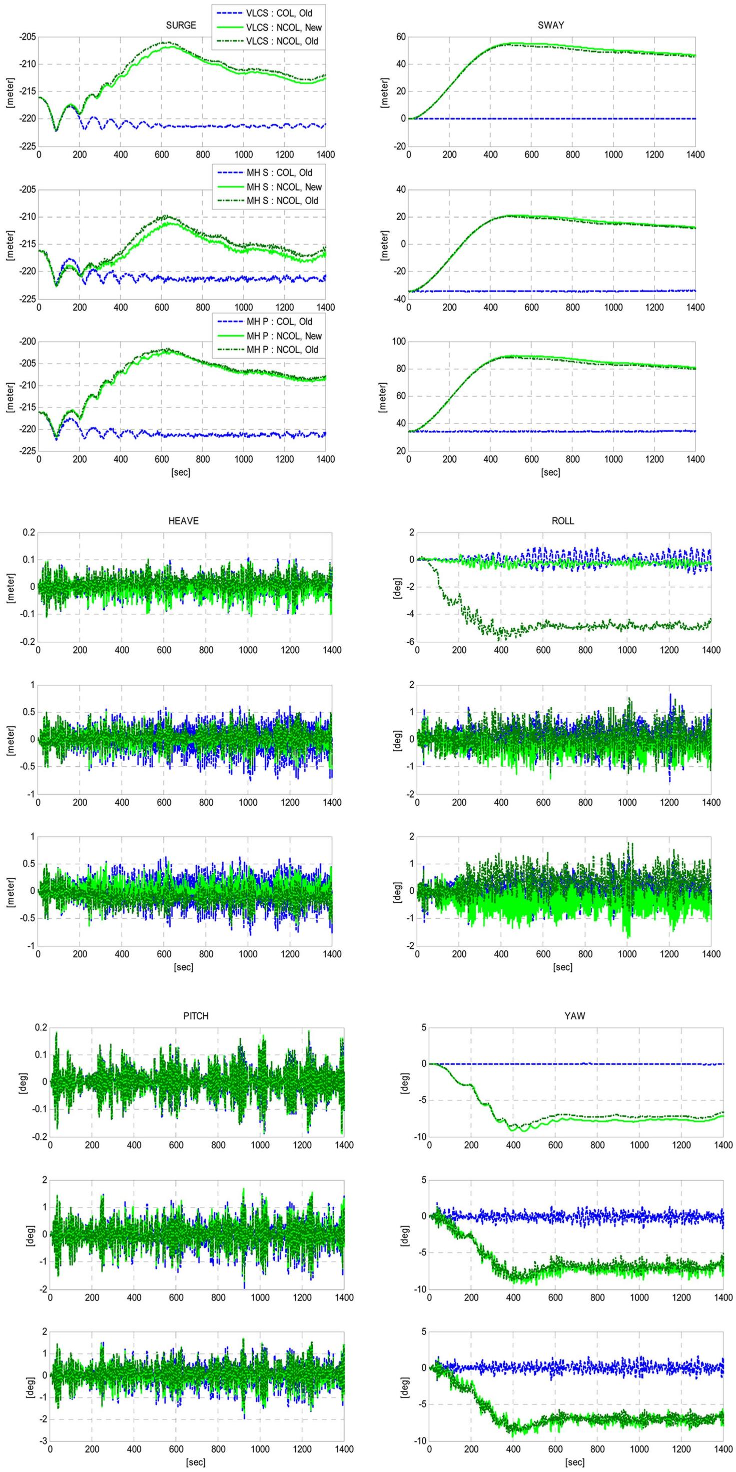


Fig. 3 Global performance of the system for collinear and non-collinear conditions

worse, the hydrostatic roll moment caused by mean yaw, $C(4,6)$, is bigger than $C(4,4)$ in the case. To remedy the undesirable situation, the KG value is decreased by 1.4 m and the LCG is adjusted by 1m to be closer to LCB in the revised design, as shown in Table 4. With the revised KG and LCG values, the dry roll natural period becomes more reasonable (Guerlay 2007) and the mean roll angle is back to zero even if there exists the same mean yaw angle in the same non-collinear environment. This example illustrates that undesirable circumstances may occur to the single-point-moored system in non-collinear environment for certain ship parameters and loading conditions, while it is not so in collinear environments. On the other hand, the magnitudes of wave-frequency responses are about the same for all the head-wave cases regardless of collinear or moderately non-collinear current and wind conditions.

3.1 Operability/robustness of the system

With the revised KG and LCG values, the operability and robustness of the crane and docking system in collinear and non-collinear environments are compared in terms of relative motions and mooring tensions.

Fig. 4 shows the 6 DOF-relative-response time histories between the container ship and mobile harbors on each side. The relative motions are of particular importance for crane operation. In case of collinear environment, the mean yaw and roll angles of the three floating bodies are close to zero and the system satisfies the maximum relative motion requirement with surge-sway-heave within ±0.8 m and roll-pitch-yaw within ±2 degrees even in sea state 4. For the non-collinear environmental condition, even if the mean yaw weathervaning by 6.5 degrees occurs, three floating bodies move together, so it does not influence their relative motions. The magnitudes of the 6DOF relative responses are about the same as those of collinear case.

Therefore, from the dynamics point of view, there is no harm in relative motions of the system even in moderately non-collinear environment, but the system may experience the unwanted situation (e.g., mean roll angle) depending on ship parameters and loading condition, as pointed out earlier.

The statistics of the 6 DOF relative motions in both collinear and non-collinear environments are given in Tables 5 and 6, which is an important measure for crane operability. In both cases, the dynamic translational and rotational motions are within operation limits (e.g., ±1 m and ±5 degrees), so the current design can be used for the given mild SS4 condition even without any dynamic control or temporary breakwater. The relative motions can further be reduced by using bilge keels and/or motion-compensation devices on MH.

Next, to check the safety of the mooring system, tension records are given in the following. Fig. 5 shows tension time histories of two bow hawsers connected to the fixed parking post for both collinear and non-collinear environments. In the non-collinear case, the port-side hawser is more active than the starboard-side one due to weathervaning mean yaw angle and the corresponding asymmetry. As a result, the maximum tension becomes as large as 1.6 MN. On the other hand, in the collinear case, the tensions on both bow hawsers are equally balanced and the maximum tension is less than 1.3MN. This results shows that the maximum tension on a bow hawser can be increased by 30% in the moderately non-collinear environment. Even in the collinear environments, if MH is docked only on one side of the container ship, the same phenomenon may happen due to the loss of geometrical symmetry.

In case of side mooring system and fender as given in Fig. 6, the collinear case gives symmetric

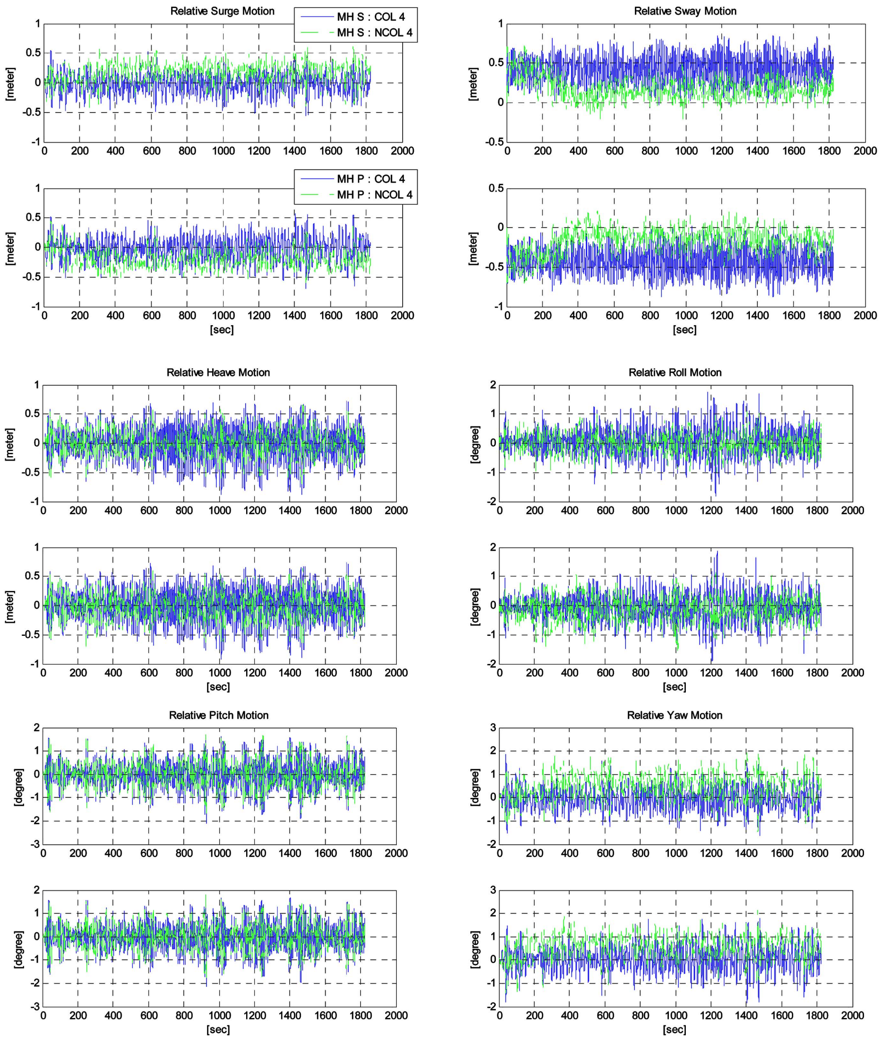


Fig. 4 Relative response time histories for 6 DOF motions (MHP = mobile harbor port side with respect to the container ship, MHS = mobile harbor star-board side) The blue (solid) line is for collinear case and the green (dash-dot) line is for non-collinear case (new)

Table 5 Statistics of the relative motions (Collinear SS4; MHS/MHP)

	Mean	Std. Dev.	Max	Min
SURGE	-0.018/-0.015	0.167/0.193	0.545/0.578	-0.553/-0.693
SWAY	0.423/-0.423	0.164/0.163	0.849/0.070	-0.038/-0.885
HEAVE	0.000/0.000	0.276/0.277	0.720/0.741	-0.880/-0.919
ROLL	0.049/-0.060	0.475/0.470	1.758/1.867	-1.810/-1.915
PITCH	-0.004/-0.004	0.591/0.595	1.668/1.677	-2.106/-2.134
YAW	-0.042/ 0.043	0.495/0.566	1.851/1.793	-1.635/-1.836

Table 6. Statistics of the relative motions (Non-Collinear SS4; MHS/MHP)

	Mean	Std. Dev.	Max	Min
SURGE	0.161/-0.186	0.168/0.157	0.631/0.454	-0.417/-0.598
SWAY	0.191/-0.174	0.141/0.155	0.719/0.209	-0.240/-0.706
HEAVE	0.006/-0.002	0.217/0.222	0.651/0.648	-0.703/-0.695
ROLL	-0.003/ -0.121	0.343/0.413	1.098/1.136	-1.202/-1.706
PITCH	-0.007/0.000	0.566/0.563	1.788/1.801	-1.807/-1.839
YAW	0.462/0.552	0.537/0.507	2.046/2.132	-1.456/-1.529

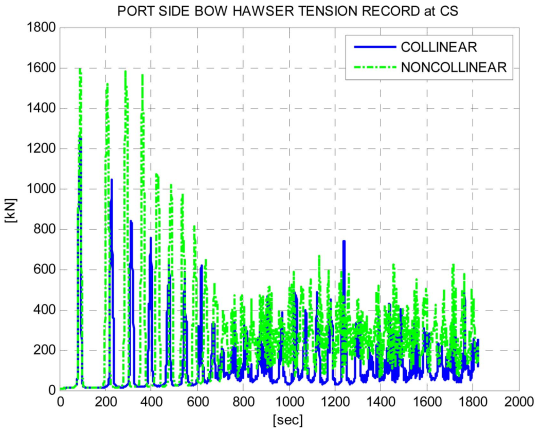


Fig. 5 Tension records for both bow hawsers

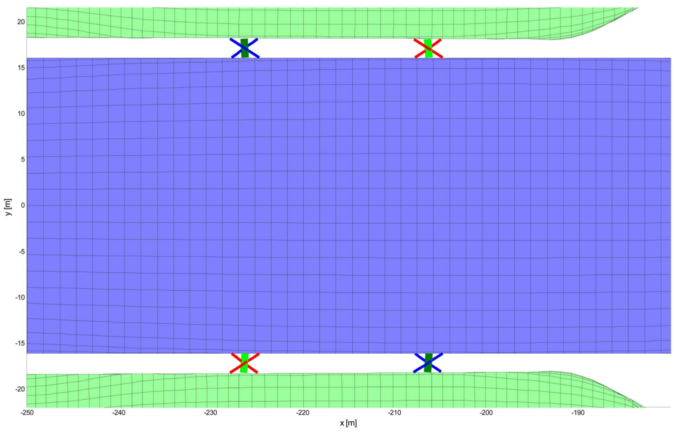


Fig. 6 Enlarged *X*-*Y* plan view of 4 sets of cross hawsers and fenders

tension records and fender reaction forces for the port- and starboard-side sets. However, the symmetry is broken in the non-collinear case, as expected; more active fender/hawser sets are given as red/dark green in the Fig. 6. For the non-collinear case, tension records and fender reaction forces of the two front sets are shown in Fig. 7. The tension is measured at connection point to container ship.

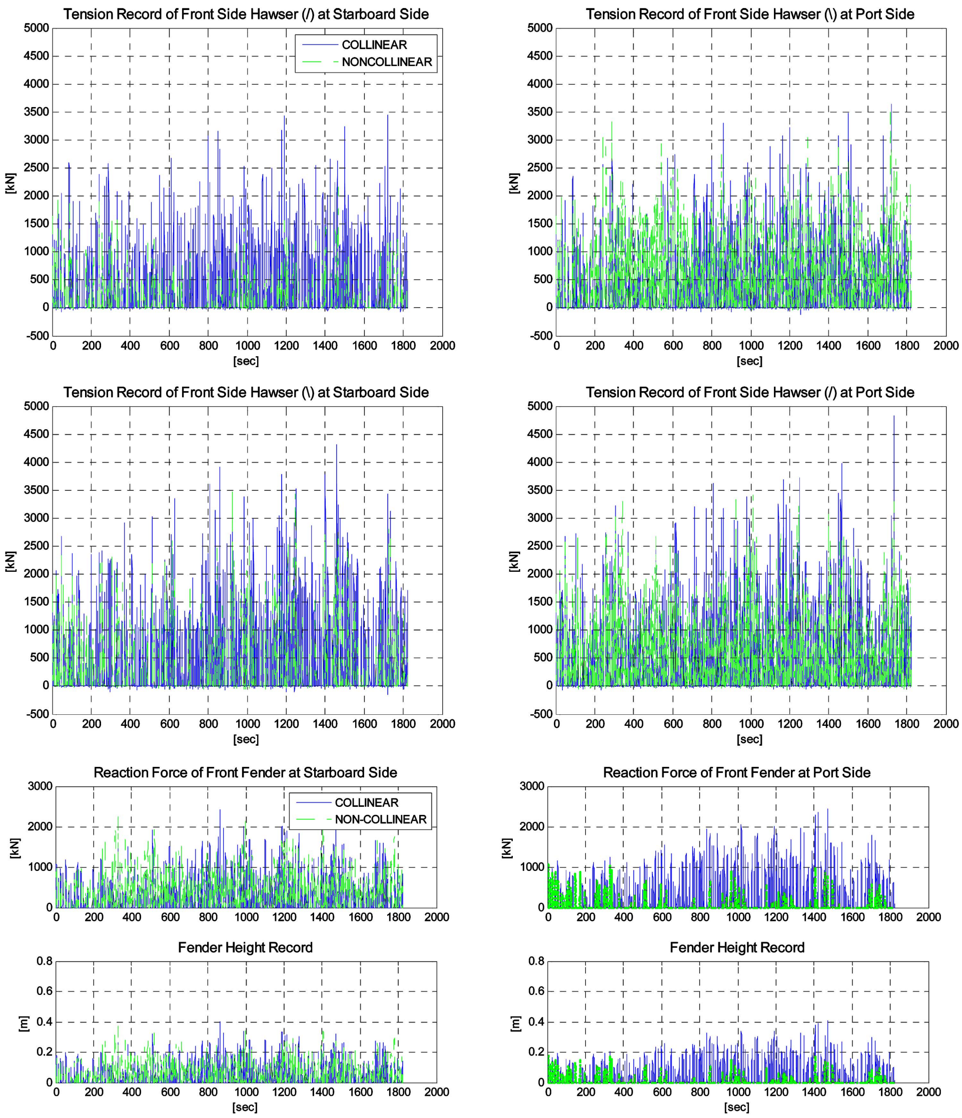


Fig.7 Time histories of side hawser tensions and fender reaction forces & fender heights

For the tensions of side hawsers, active sets in non-collinear case show correspondence to collinear case results with overall peaks at 3 ~ 3.5 MN and maximum at 4.8 MN. Meanwhile, inactive groups in non-collinear case present reduced tension records as much as about 0.5 ~ 1 MN. When the animation of side hawsers is examined, they repeat slack and taut responses depending on the relative sway motions. When they become taut, snap loading occurs on the hawsers, as can be seen in Fig. 7. Furthermore, in non-collinear case fender generated larger reaction force for inactive hawser set, while elongated distance with the active hawser set reduced fender activation significantly to half or zero. For active fenders in non-collinear case or overall fenders of collinear case have average peaks at 1.3 MN with maximum 2.5 MN.

4. Conclusions

Hydrodynamic interactions among three single-point-moored floating bodies, a container ship and two mobile harbors on both sides, with bow hawsers and 8 side hawsers and 4 fenders in port- and starboard-side gaps are investigated by using the multi-vessel-mooring coupled dynamic analysis program in time domain. It is assumed that the containership is docked to a fixed mono-pile station through two bow hawser lines. Both collinear and non-collinear wind-wave-current mild-sea-state-4 environments are considered. In both cases, the crane operability was checked by calculating the relative 6DOF motions between the container ship and the two mobile harbors. The relative motions turned out to be acceptable within the crane operational limits. However, in the non-collinear environment, there exists mean yaw to weathervane and one of the two bow hawsers is loaded more due to the loss of symmetry. In this case, mean roll may also occur depending on hull weight distribution and loading condition, which will harm smooth crane operation. With the current simulation technique, the operability and robustness of the single-point-moored multi-vessel system with many hawser lines can thoroughly be investigated.

If waves come from other than head direction in non-collinear environment, the system may impose more dynamic problems and more studies are needed in this regard. The possible dynamic problem may further be remedied by motion-suppression devices or with DP control, which can also be realized in the current fully coupled time-domain simulation technique.

Acknowledgements

This study is financially supported by KAIST's (Korea Advanced Institute of Science and Technology) Mobile Harbor Program.

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