Diffraction and Radiation of Waves Around Side-by-Side Moored Vessels

R.H.M. Huijsmans (MARIN)
J.A. Pinkster (TUD)

Report 1300-P **17-22 June 2001**

Published in the Proceedings of the 11th International Offshore and Polar Engineering Conference, Stavanger, Norway, Volume I, ISOPE, ISBN 1-880653-51-6 (Set)

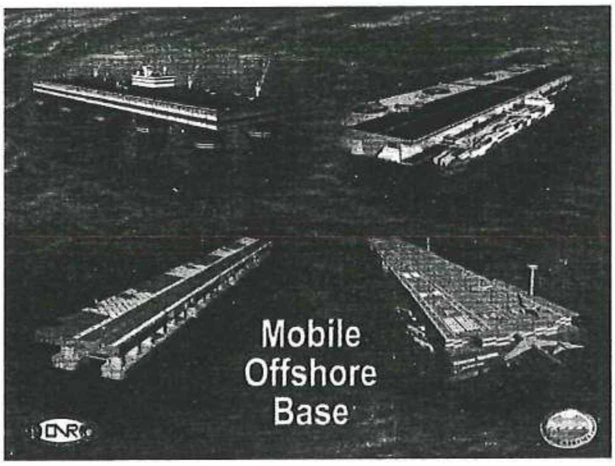
TU Delft
Delft University of Technology

Faculty of Mechanical Engineering and Marine Technology
Ship Hydromechanics Laboratory

The Proceedings of
The Eleventh (2001) International
OFFSHORE AND POLAR ENGINEERING CONFERENCE

Stavanger, Norway

VOLUME I, 2001



ISOPE International Society of
Offshore and Polar Engineers

International Standard Book Number: ISBN 1-880653-51–6 (Set)
ISBN 1-880653-52–4 (Vol. I)
International Standard Serial Number: ISSN 1098-6189 (Set)

Cooperating Organizations:

Canadian Association of Petroleum Producers (CAPP)
American Society of Civil Engineers (ASCE) - Engineering Mechanics Division
Korea Committee for Ocean Resources and Engineering (KCORE)
Canadian Society of Civil Engineers (CSCE) - Engineering Mechanics Division
Chinese Society of Ocean Engineers (CSOE)
Chinese Society of Naval Architects and Marine Engineers (CSNAME)
Chinese Society of Theoretical and Applied Mechanics (CSTAM)
Russian Academy of Sciences (RAS)
Singapore Structural Steel Society (SSSS)
Norwegian Petroleum Society (NPF)
The Institution of Engineers Australia (IE Australia)
Kansai Society of Naval Architects, Japan (KSNAJ)
IRO (The Netherlands)
Technical Research Centre of Finland (VTT)
The Society of Materials Science, Japan (JSMS)
The Offshore Engineering Society (OES), United Kingdom
Ukraine Society of Mechanical Engineers (USME)
IFREMER, France
Scott Polar Research Institute (SPRI), UK
The Institute of Engineers Indonesia (PII)
Brazilian Society of Naval Architects and Marine Engineers (SOBENA)
Korean Society of Civil Engineers (KSCE)

Printed and bound in USA

Proceedings of the Eleventh (2001) International Offshore and Polar Engineering Conference
Stavanger, Norway, June 17–22, 2001

ISBN 1-880653-51–6 (Set); ISBN 1-880653-52–4 (Vol. I); ISSN 1098-6189 (Set)

Diffraction and Radiation of Waves Around Side-by-Side Moored Vessels

R.H.M. Huijsmans
Maritime Research Institute Netherlands
Wageningen, The Netherlands

J.A. Pinkster and J.J. de Wilde
Technical University Delft
Delft, The Netherlands

Abstract

This paper investigates the hydrodynamical aspects of a floating two body system. The emphasis is geared to a side by side mooring of a FPSO vessel and a LNG carrier. The main focus is on the following issues:

- Determination of the mean and low frequency wave drift forces for multi–body systems
- Development of a robust linear potential solver for multi–body systems

In the paper a lid technique will be presented to circumvent unrealistic high water velocities on the ship's hull. Also the accurate integration of the complete Green's function will be highlighted.

Key words

Linear Hydrodynamics of Multi body systems , Green's function, Integration accuracy

1 Introduction

In the present-day development of offshore activities there is an increasing interest in the behavior of multi-body systems. One example of such a system is a floating oil or gas production annex storage facility, to which an export tanker is moored during loading operations. When evaluating the feasibility of such a system, attention will be focussed on the motions of both the production platform and the tanker and the forces in the moorings and the relative motions of loading arms. Interaction effects will be present in the second order wave drift forces. The narrow spacing between the two adjacent vessels is an added complexity, both with respect to wave loading and dynamical response. A frequently used option in relation to multiple body computations has so far been to use single body hydrodynamics input, i.e. to ignore the effects of hydrodynamical interaction between the different bodies. The more general problem of how to establish convergence for hydrodynamical coefficients for multiple body systems is also discussed throughout the paper. Particular emphasis is put on low frequency excitation forces, which for multiple bodies have to be computed by integration of the local body pressure. The alternative option of using momentum conservation methods to obtain the global forces is not applicable in the case of multiple bodies, since this approach rests on computing the momentum flux at "distant" control surfaces. Finally, since the present paper is dedicated specifically to multiple body hydrodynamics, the motion dynamics of multiple body systems is only discussed in more general terms.

The actual importance of the interaction effect depends on the configuration of the multi body system, the size of the floating bodies, and the separation distance.

This paper discusses the hydrodynamic interaction effects in the first order motions of, and the mean second order drift forces on two vessels, i.e. a FPSO and a LNG carrier which are floating freely in regular waves. Inoue [4] also reported results of a FPSO – LNG carrier mooring arrangement. For the determination of the mean wave drift forces he used a momentum approach. Nori [9] reported an extension of this formulation to multi–body systems. A similar extension was also reported by Liu [7]. This momentum approach however is unsuitable for the calculation of the low frequency wave drift forces, when applied to mooring systems with an natural period that is not very low. In this study use is made of a pressure integration technique for the determination of the mean and low frequency wave drift forces (see Pinkster [11]). This approach was extended to multi body systems by Oortmerssen [10]. In the use of the pressure integration technique for the calculation of the wave drift force, the water velocities on the ship's hull play an important role. This is due to the quadratic effect of the water velocities as seen from Bernoulli's equation. Side-by-side moored vessels are positioned in the close proximity of one another. In linear potential flow calculations this may lead to large water velocities between the two vessels. These large water velocities will in practice be limited by either viscous effects or other non–linear effects. It is essential to develop a robust linear potential flow solver applicable to multi–body systems. To limit the unrealistic high water velocities a lid approach was used to cover the free surface in-between the two vessels. Visual observations from model tests of the FPSO with the LNG carrier (see Buchner et al [1]) has led to the understanding that the fluid flow in between the two vessels does not show large resonant behavior. In our approach the fluid flow between the two vessels is treated as an internal flow in the ship. The lid technique used is similar to the lid techniques used for irregular frequency suppression, due to the fact that we limit the internal fluid flow between the two vessels. A description of this irregular frequency suppression technique is e.g. reported by Huijsmans [13].

In a side by side mooring study of two types of offshore constructions (Workover vessel and a TLP) Teigen [15] showed that in order to have satisfactorily converged solutions of the wave drift forces, computed with a low order diffraction solver, one needs to use a very large number of panels. For single body applications Newman and Lee presented the sentitivity of the wave loads with respect to the discretization of the body [8] To use very high number of panels is still not a viable option in the current design practice. Although promising techniques, like the pre–conditioned FFT solver from Korsmeyer [5], Scorpio et al [14] and Kring et al [6] have been reported. In order to avoid going to very high numbers of panels, attention is paid to the integration of the Green's function over a panel.

In another paper by Buchner et al [1] attention will be paid to the time domain description of the motions of multi-body systems.

2 Numerical Model

2.1 Gauss Quadrature

For the determination of the pressures and velocities on the mean wetted surface of the vessel use is made of a standard linear diffraction code (see e.g. Huijsmans ([13], [3] and Pinkster [12] for a short description) . In single body as well as in multi body systems calculations, the evaluation of the Green's function in points on the ship's hull require an exact integration of the Rankine part of the Green's function. The wave part of the Green's function is integrated using an Euler scheme. The rankine part of the Green's function is integrated exactly using e.g. Fang [2].

We re–iterate the following observations with respect to the computational complexity for two body systems as was made by Teigen [15]:

Due to possible loss of symmetry and corresponding increase in the number of panels required, the additional computational effort involved in a n–body computations may be significant, as compared to a single body. Consider e.g. two identical bodies, each with two planes of symmetry, but arranged in such a way that no global plane of symmetry exists. The number of panels required for such a system, given that an "equivalent" discretization is used, will increase by a factor of 8 relative to a single body. As the computation time for diffraction calculations is roughly proportional to the number of panels squared, the practical consequences in terms of computer resources and run-times are some times quite formidable.

It is however the nature of multi–body hydrodynamics especially for vessels moored side by side that the integration of the wave part of the Green's function using an Euler scheme is no longer sufficient. The source strength however is still assumed to be constant over a panel.

$$\phi(\vec{x}) = \int_S \sigma(\vec{a}) G(\vec{x}, \vec{a}) dS$$

In which $\sigma(\vec{a})$ describes the source strength and $G(\vec{x}, \vec{a})$ is the Green's function, written as:

$$G(\vec{x}, \vec{a}) = \frac{1}{|\vec{x} - \vec{a}|} + f(\kappa, \vec{x}, \vec{a})$$

with $f(\kappa, \vec{x}, \vec{a})$ is the wave part of the Green's function.
Or discretized using an Euler summation:

$$\begin{aligned} \phi(\vec{x}_j) &= \sum_{i \neq j} \sigma(\vec{a}_i) G(\vec{x}_j, \vec{a}_i) \Delta S_i + \\ & \lim_{i \to j} \int_{\Delta S_i} \frac{1}{|\vec{x}_j - \vec{a}_i|} dS + f(\kappa, \vec{x}_j, \vec{a}_j) \Delta S_j \end{aligned}$$

In case of two bodies very close to one another one cannot use the Euler approach for the integration of the wave part of the Green's function. This should be replaced by e.g. a 4 point Gauss Quadrature integration rule, which then reads:

$$\begin{aligned} \phi(\vec{x}_j) &= \sum_{i \neq \Omega_j} \sigma(\vec{a}_i) G(\vec{x}_{\Omega_j}, \vec{a}_i) \Delta S_i + \\ & \lim_{i \to \Omega_j} \int_{\Delta S_i} \frac{1}{|\vec{x}_{\Omega_j} - \vec{a}_i|} dS + \sum_{k=1}^{4} w_k f_k(\kappa, \vec{x}_{\Omega_j}, \vec{a}_k) \end{aligned}$$

In which w_k are the Gauss Quadrature coefficients and were Ω_j describes the area were the Gauss Quadrature is applied. Here $\vec{a}_k$ is the position of the collocation point in the subdivided panel. Typically we take a radius of 4 times the diameter of the panel to limit the area Ω_j. A more rigorous approach would be to separate the free surface mirror image part of the wave part of the Green's function $f(\kappa, \vec{x}, \vec{a})$. This mirror part can then be integrated exactly in the same way as the regular rankine part of the Green's function. This however was not attempted in this study.

2.2 Lid Approach

In the analysis of the fluid flow in between the two vessels we postulate that no resonance phenomena will occur. However applying linear potential theory in the direct vicinity of the two vessels will lead to an overestimation of the water velocities. In order to arrive at a more realistic flow condition using a linear potential solver a lid is applied on the free surface in between the two vessels. Thereby indicating that the free surface in between the two vessels is a integral part of the interior of the two vessels. Therefore a lid technique is applied that originates from the irregular frequency suppression technique. One must bear in mind that a lid is applied such that it has a minimum disturbance of the outer flow of the two vessels. Alternatively one could use a boundary condition on the free surface lid proportional to the displacement and or proportional to the velocity. Representing a spring and damper alike restoring characteristic of the free surface lid. In our approach this has not been attempted because of the arbitraryness of the choice of the spring and damping constants. The integral equations that are postulated for the interior free surface read:

$$\begin{aligned}
-2\pi\sigma(\vec{x}) \quad &+ \quad \int_S \sigma_S(\vec{a})G(\vec{x},\vec{a})dS \\
&+ \quad \int_F \sigma_F(\vec{a})G(\vec{x},\vec{a})dS \\
&= \quad (\vec{v}\cdot\vec{n}),\ \vec{x} \in \text{Ship's hull} \\
+4\pi\sigma(\vec{x}) \quad &+ \quad \int_S \sigma_S(\vec{a})G(\vec{x},\vec{a})dS \\
&+ \quad \int_F \sigma_F(\vec{a})G(\vec{x},\vec{a})dS \\
&= \quad 0,\ \text{On free surface between the vessels}
\end{aligned}$$

Here S describes the surface of the LNG and FPSO vessel and F signifies the free surface respectively.

3 Results

3.1 Gauss Quadrature

In order to get an impression of the accuracy of the evaluation of the Green's functions and its horizontal and vertical derivatives indicated as GR and GZ, a comparison of the real parts is presented in Figures 1 to 3. The displayed variable names ending with an E indicate the Euler integration over a panel and the Q signifies the Gauss Quadrature approach. Panels were chosen of dimensions 4x4 m respectively 10x10 m, with centroid situated at (0,2.,-2.) and (0,5.,-5.) respectively with a normal direction of (0.,1.,0.). The field point was chosen varying along the x-axis from 0.01 up to 10. m The wave frequency was chosen at 1.0 rad/sec. The FINGREEN subroutine from the WAMIT program is used for the Green's function evaluations.

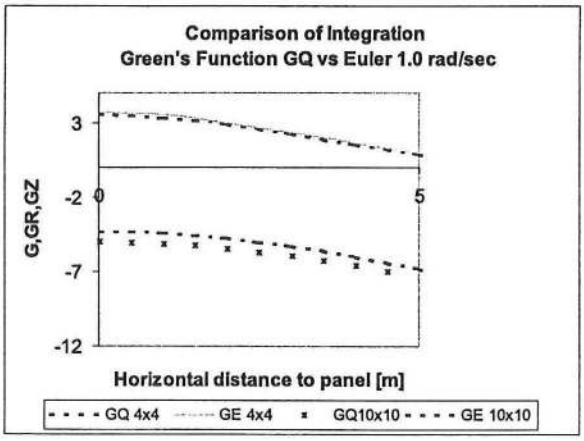


Figure 1: *Influence of integration scheme on accuracy of Green's function evaluation*

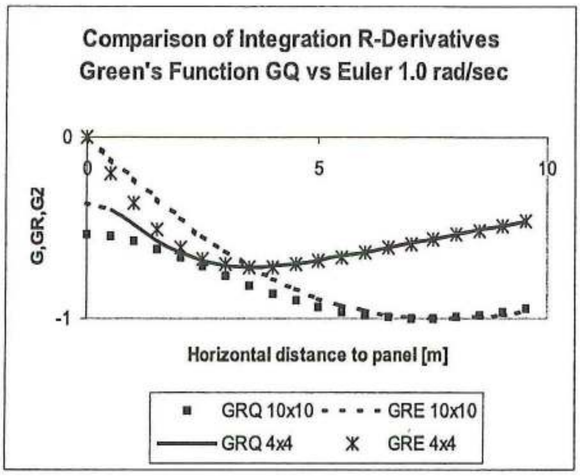


Figure 2: *Influence of integration scheme on accuracy of horizontal derivative of Green's function evaluation*

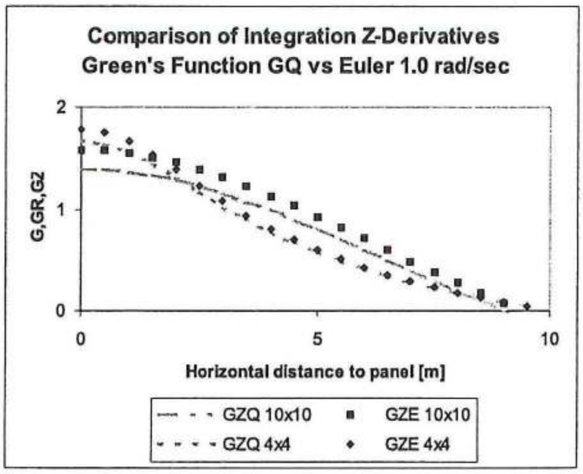


Figure 3: *Influence of integration scheme on accuracy of vertical derivative of Green's function evaluation*

3.2 FPSO and LNG Carrier

In the following section results of computations and model test experiments will be presented.
The overall dimensions of the LNG carrier and the FPSO tanker are displayed in Table 1.

Table 1 – Particulars of the LNG carrier and FPSO tanker

A panel description of the two vessels is depicted in Figure (4). The distance between the two vessels was 4.0 m apart. For the validation the following conditions were applied:

- from 0 to 360 degrees wave heading in steps of 15 degrees. However here only the windward beam sea case to the LNG carrier will be discussed.

Designation	Symbol	Unit	FPSO	LNG
Length between perpendiculars	L_{pp}	m	332.	274.
Breadth	B	m	70.	44.2
Draft	T	m	14.50	11.
Displacement volume	∇	m3	331,700	99,500
Longitudinal Center of gravity (stat. 10)	LCG	m	-5.47	-1.06
Center of gravity above keel	VCG	m	14.2	16.3
Metacentric height transverse	GM_t	m	20.2	4.7
Pitch radius of gyration in air	k_{yy}	m	83.0	68.5
Roll radius of gyration in air	k_{xx}	m	25.9	15.2
Natural roll period	T_ϕ	s	14.7	16.0

Table 1: Main Particulars of FPSO and LNG Carrier

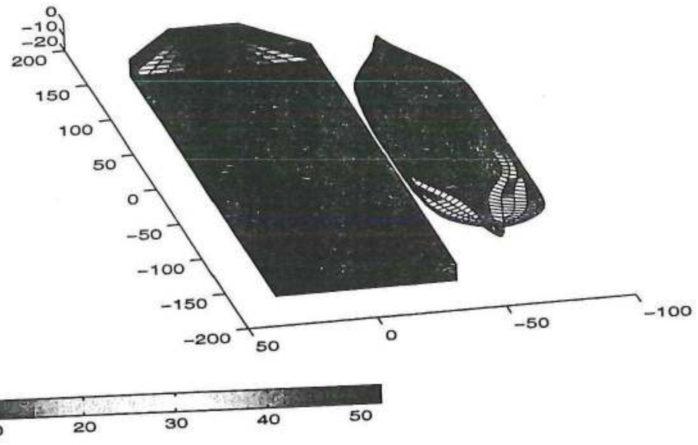


Figure 4: *Panelization of FPSO and LNG Carrier with 2468 Panels in total.*

- speed Fn=0.0
- panelizations of the two bodies is 2468 panels in total
- with use of Gauss Quadrature on the Green's function integration
- lid approach

Motion RAO is depicted in Figure 7 to 9. Also the added mass in heave including the coupling with pitch is presented in Figure 5 and Figure 6.

Also wave drift computations were performed for the single body cases (FPSO and LNG carrier) for the comparison of the influence of the interaction effects. In Figures 10 and 11 the interaction effects and the effect of the representation of the two body fluid flow in the mean wave drift force for the LNG carrier in windward beam waves are displayed. Here also the results for the free floating LNG carrier without the presence of the FPSO are depicted in these Figures.

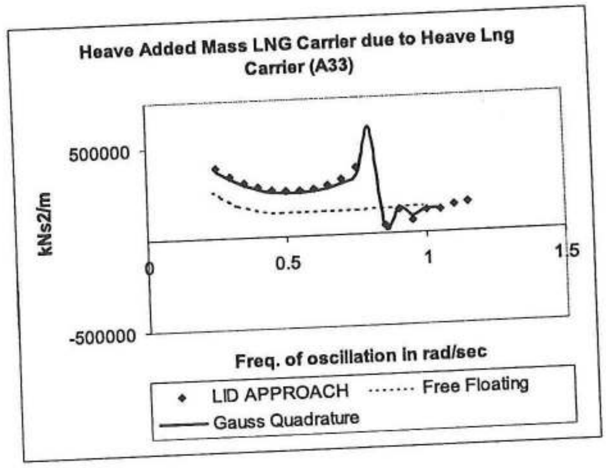


Figure 5: *Comparison Lid approach and Gauss Quadrature for heave added mass on LNG carrier*

4 Discussion

4.1 Accuracy

From the Figures 1 to 3 the accuracy of the Green's function evaluation using the Gauss Quadrature approach, we see that the horizontal derivatives in this case differ significantly from the Euler approximation once the point of observation is close

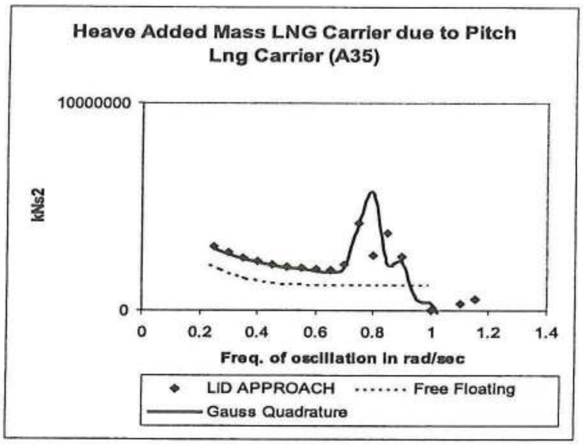


Figure 6: *Comparison Lid approach and Gauss Quadrature for heave added mass on LNG carrier*

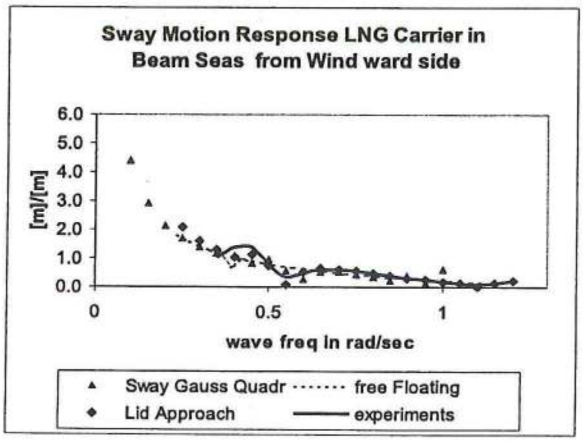


Figure 7: *Comparison between Single and interaction effects for the LNG carrier*

to the panel. After a distance of one to two times the diameter of the panel the Euler approximation coincides with the Gauss Quadrature approach. The effect of different panel size as displayed in Figure 2 is mostly due to the submergence of the centroid of the panel (from (0,1,-1) to (0,5,-5)). The vertical derivative of the Green's function also displays differences for the two approaches once the field point is near the panel surface.

4.2 Hydrodynamic Results

In former studies the multi body hydrodynamics were often determined using free floating single body hydrodynamics. In the Figures 5 to 11 the added mass, motion response and mean wave drift forces results for the LNG carrier show that this simplification is not allowed for side by side moored vessels in close proximity of one another. The lid and Gauss Quadrature approach give only slight differences for the heave added masses

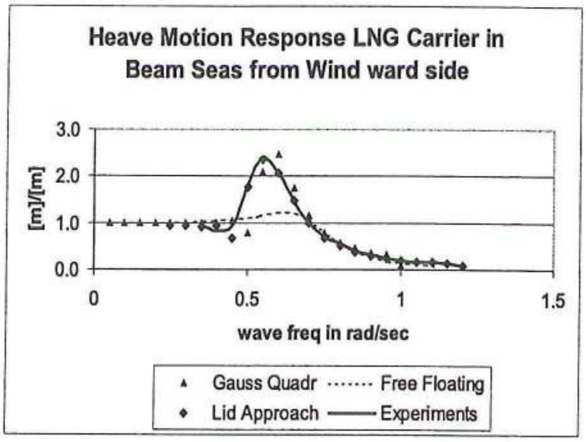


Figure 8: *Comparison between Single and interaction effects for the LNG carrier*

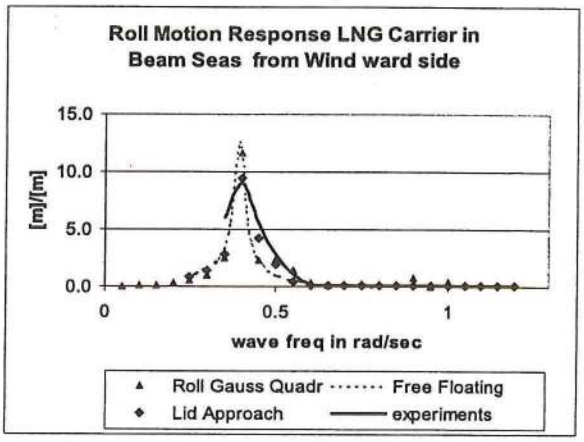


Figure 9: *Comparison between Single and interaction effects for the LNG carrier*

a_{33} and a_{35} at wave frequencies between 0.7 rad/sec and 0.85 rad/sec. The heave motion response of the LNG carrier shows that due to the presence of the FPSO, the heave RAO at resonance is enhanced by at least a factor 2. The latter is due to the reflection of the waves on the FPSO and the radiated waves from the FPSO. Here one also observes that the lid and Gauss Quadrature approach are in quite good agreement with the results of the model tests. The results of these model tests are discussed in more detail by Buchner et al [1]. For the determination of the roll response also a viscous damping coefficient was added to the equation of motion. (see Figure 9). The resulting roll RAO of the LNG carrier from the model test is not very much influenced by the presence of the FPSO. A more drastic difference between single and multi body hydrodynamics is seen from the results of the mean wave drift forces in surge and sway. (see Figure 10 and 11). The mean surge wave drift force in beam seas differs from the single body computations by more then a factor 2 to 3 in the wave frequency range 0.75 to

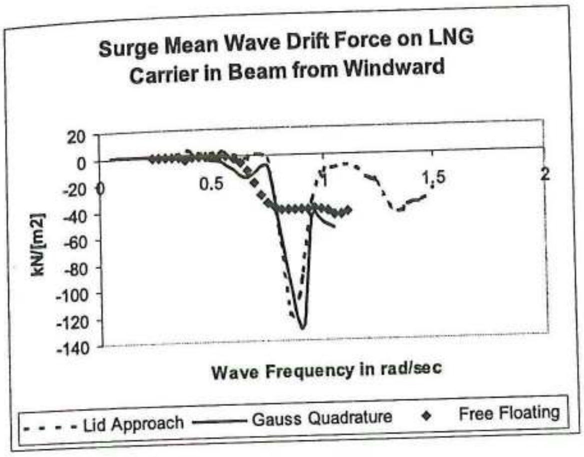


Figure 10: *Comparison between Single and interaction effects for the LNG carrier*

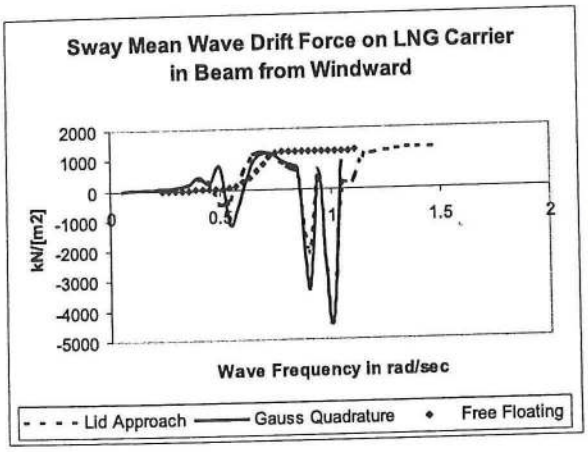


Figure 11: *Comparison between Single and interaction effects for the LNG carrier*

0.90 rad/sec. Here one also observes a good agreement between the lid and Gauss Quadrature approach. The results from the mean wave drift force in sway exhibit a large discrepancy with single body results. Two distinct negative peaks in the mean sway drift force RAO at wave frequency 0.85 to 1.0 rad/sec are observed. A conclusion with respect to the agreement between the lid approach and the Gauss Quadrature approximation is not easily attained. The lid approximation hinges strongly on the physical description of the fluid flow between the two vessels, whereas the Gauss Quadrature approximation directly is related to the accuracy of the integration of the Green's function.

5 Conclusions

From this study it is evident that simulations for multi body systems in a side by side arrangement can not be based on single body hydrodynamics. Mutual hydrodynamic interaction between the two vessels must be accounted for. As a result the multi body hydrodynamics often suffer from inaccuracies when calculated using standard linear diffraction codes. This is mainly due to the lack of sufficient number of panels in the geometric description of the two bodies. Unfortunately this deficiency is not easily overcome.

The use of a higher order integration scheme on the wave part of the Green's function with respect to the standard Euler integration scheme is mandatory for the simulation of the motions of vessels in a side by side mooring arrangement.

References

[1] B. Buchner, A. van Dijk, and J. J. de Wilde. Numerical multiple body simulations of side by side mooring to an fpso. In *Proceedings of the 11th ISOPE Conf.*, 2001.

[2] Fang Zhong-Sheng. A new method for calculating the fundamental potential functions induced by a source/dipole polygon. *Applied Mathematics and Mechanics*, 6(7), July 1985.

[3] R.H.M. Huijsmans, J.H Westhuis, and A. Ballast. Non–linear diffraction around heeled ship sections. In *Proceedings of the 9th ISOPE Conf.*, 1999.

[4] Y. Inoue and M. Islam. Relative motions of multiple floating offshore structures. In *Proceedings of the OMAE conference*, 1999.

[5] T. Korsmeyer, J. Klemas, T. Philips, and J. White. Fast hydrodynamical analysis of large offshore structures. In *Proceedings of the 9th ISOPE Conf.*, 1999.

[6] D Kring, T. Korsmeyer, J. Singer, D. Danmeier, and J. White. Accelerated non-linear wave simulations for large structures. In *Proceedings of the 7th Int. Conference on Num. Ship Hydrodynamics*, 1999.

[7] X.Q. Liu. *Dynamics of surface towed flexible pipelines and mean wave drift loads on floating flexible structures.* PhD thesis, University of Manoa Honolulu, 1998.

[8] J.N. Newman and C.M. Lee. Sensitivity of wave loads to the discretization of bodies. In *Proceedings of Boss 1992 Symposium*, 1992.

[9] N. Nori. A study of hydrodynamic pressures and wave loads on three dimensional floating bodies. *IHI Engineering Review*, 1994.

[10] G. van Oortmerssen. Some hydrodynamical aspects of multi–body systems. In *Proceedings of the Int. Symp. on Hydrodynamics in Ocean Engineering*, 1981.

[11] J.A. Pinkster. *Low frequency second order wave exciting forces on floating structures.* PhD thesis, Technical University of Delft, 1980.

[12] J.A. Pinkster. Hydrodynamic interaction effects in waves. In *Proceedings of the 5th ISOPE Conf.*, 1995.

[13] R.H.M.Huijsmans. *Mathematical modelling of the mean wave drift force in current; a numerical and exprimental study.* PhD thesis, Technical University of Delft, 1996.

[14] S. Scorpio, R. Beck, and T. Korsmeyer. Non–linear water wave computations using a multipole accelerated, desingularized method. In *Proceedings of the 21th Naval Hydrodynamics Symposium*, 1998.

[15] P. Teigen. Numerical aspects of multiple body hydrodynamics. In *Proceedings of the 10th ISOPE Conf.*, 2000.