Challenge of Hydrodynamic Analysis for a Structure in Waves

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Abstract

Hydrodynamic analysis is one of the key steps in safety assessment of a structure in waves. Many options are available for answering challenge raised from marine and offshore energy industry, from costly three dimensional CFD to the efficient but not perfect boundary element models. Focus on the boundary element methods, analysis methods for the interaction of waves and structures are discussed. Those boundary element models cover frequency domain and time domain, linear and non-linear. Special attention is pay to the problems encountered in those models and approaches we adopted for their engineering solution.

Keywords: Boundary element method, Frequency domain, Time domain, Linear, Non-linear, multi-level.

Introduction

Hydrodynamic analysis with reliable accuracy is the first step in a successful structure assessment. This analysis in marine and offshore industry is usually dominant by the interaction of ocean waves and floating or fixed structure, and it seeks for a solution of a gravitational water wave field in an infinite fluid domain around the structure. Varies numerical methods have been applied in this industry area, such as RANS, SPH, Rankin source distribution method, Green's function based boundary integration method, and so on. They can be categorized in CFD method class and boundary element method (BEM) class. RANS, as the typical CFD method, is the most robust method in this area. It performs the time domain simulation and has the capability to solve most of the problems, but the high computation cost is still the main obstacle to allow it been used in routine seakeeping analysis for design and design appraisal. Comparing to CFD model, boundary element class is efficient and has different models for analysis in time domain and frequency domain, and for analysis of linear and non-linear problems. The most efficient tool in this class is the Green's function based linear frequency domain model. It can solve a few thousands of regular wave cases in one day on a high-end laptop. To take advantage of this efficient, time domain boundary element tool based on frequency domain analysis results is developed to capture the so-called geometry non-linear which dominants the solution of ship/offshore-structure response in large waves. The most expensive boundary element tool is the Rankin source/panel model which can solve nonlinear seakeeping problem and has higher uncertainty and human effect in model setting, but it is still much cheaper in use comparing to CFD models. What numerical model should be applied for a specific problem is the question that every engineer needs to answer. How to extend the existing model for more complicate analysis is the challenge for researchers in industry. In this paper, we discussed some of practices in Lloyd's Register dealing with linear and nonlinear hydrodynamic assessment.

Nonlinear Viscous Damping in Potential Flow Modeling

Frequency domain BEM model is a linear analysis tool because hydrodynamic forces in this model, like wave exciting force, wave making added-mass and damping, are linear. On the other hand, non-linear factors can be involved in ship motion equation as external force and modify the results of hydrodynamic pressure and load with effects of the nonlinear factor. A typical example is the viscous roll damping. For roll motion, wave making added-mass and damping is not the dominant component for ships with conventional hull form and the hydrodynamic force from viscous flow becomes important. A common approach is to enforce a nonlinear viscous damping moment in roll motion equation to correct the motion prediction. An analysis example is shown in Figure 1. The normalized roll motion result without viscous roll damping (VRD) is plotted in the left plot of the figure. Blue marks show the experimental data and red line is from the computation of WAVELOAD-FD, a seakeeping analysis software package of Lloyd's Register. The predicted roll motion peak at the roll natural frequency is of 32.5 and 15 times larger than the experimental observation. After adding the VRD effects in WAVELOAD-FD model, the predicted roll motion is in a good agreement with the observation as shown by the red line in the middle plot of the figure. The non-linear Ikeda roll damping model is applied in this example. In the right plot of this figure, the pressure distribution on surface of hull and bilge keel is presented at a time when the ship is rolling counter-clock wise. The orange colour indicates a higher pressure area and the light blue for the lower pressure area. The non-linear viscous damping is involved in the pressure computation.

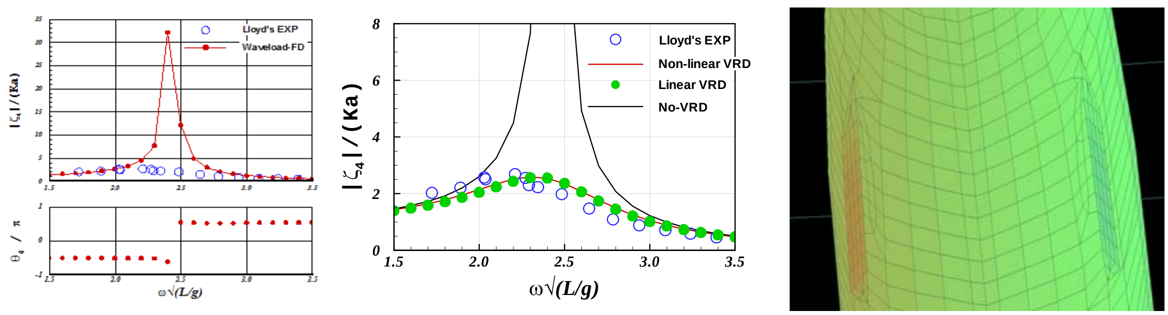

Figure 1. Nonlinear viscous damping in roll motion from a boundary element model
Left: without VRD; Middle: with VRD; Right: Pressure on hull and bilge keel

This example demonstrates that some nonlinear factor can be correctly taken into account in linear BEM model. For this viscous roll damping case, a further study revealed that the VRD can also be represented by an equivalent linear roll damping model as shown by the green marks in the middle plot of Figure 1.

Viscous flow damping also plays import role on structures with tubular members, like some offshore rags and pipelaying vessels. A pipelaying vessel assessment is used here to demonstrate a combination of nonlinear hydrodynamic model and linear boundary element seakeeping approach. Viscous flow will affect not only the roll but also other motion modes for this case. The panel model of the vessel with the stinger is shown on right of Figure 2, and the stinger configuration and force definition are presented on left of the figure.

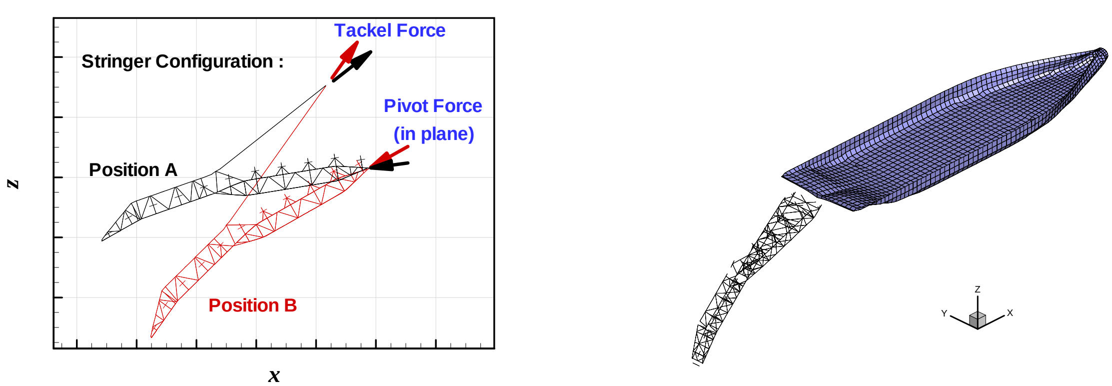

Figure 2. Model of a pipelaying vessel with stinger
Left: two position of the stinger; Right: under water part of the vessel and stinger

A CFD model for this problem will not be a practice choice and a model based on nonlinear Morrison formula would be considered. The force in the normal plane of each tubular member can be estimated from the relative velocity and acceleration between the structure motion and the flow around it. It is easy to compute this Morrison force for a fixed structure, but not for a floating one, as the vessel motion and Morrison force are coupled. In many available codes, the Morrison force model is involved in time domain BEM model. The time domain boundary element computation takes much shorter time than a CFD analysis, but its computing time is still beyond the acceptable level for design or design appraisal work. To answer the requirement, a Morrison force model module has been added in the frequency domain BEM code of Lloyd's Register, WAVELOAL-FD. The solution of this Morrison force coupled analysis is obtained from an iteration process. The Morrison force is treated as an external force in ship motion equation. In the first iteration, ship motion is obtained without Morrison force and then this ship motion is used to compute the first estimation of the Morrison force; the computed Morrison force is taken into account in ship motion solution of second iteration and repeat the 1st or previous iteration computation again for the new Morrison force. This iteration continues until both ship motion and Morrison force converged. Motion RAO of the vessel at zero ship speed and 150 degrees of heading is shown in Figure 3. The stinger decreases the ship motion and shifts the natural frequency of roll and pitch to high frequency side, and obviously the Morrison force coupling effect needs to be considered in the analysis.

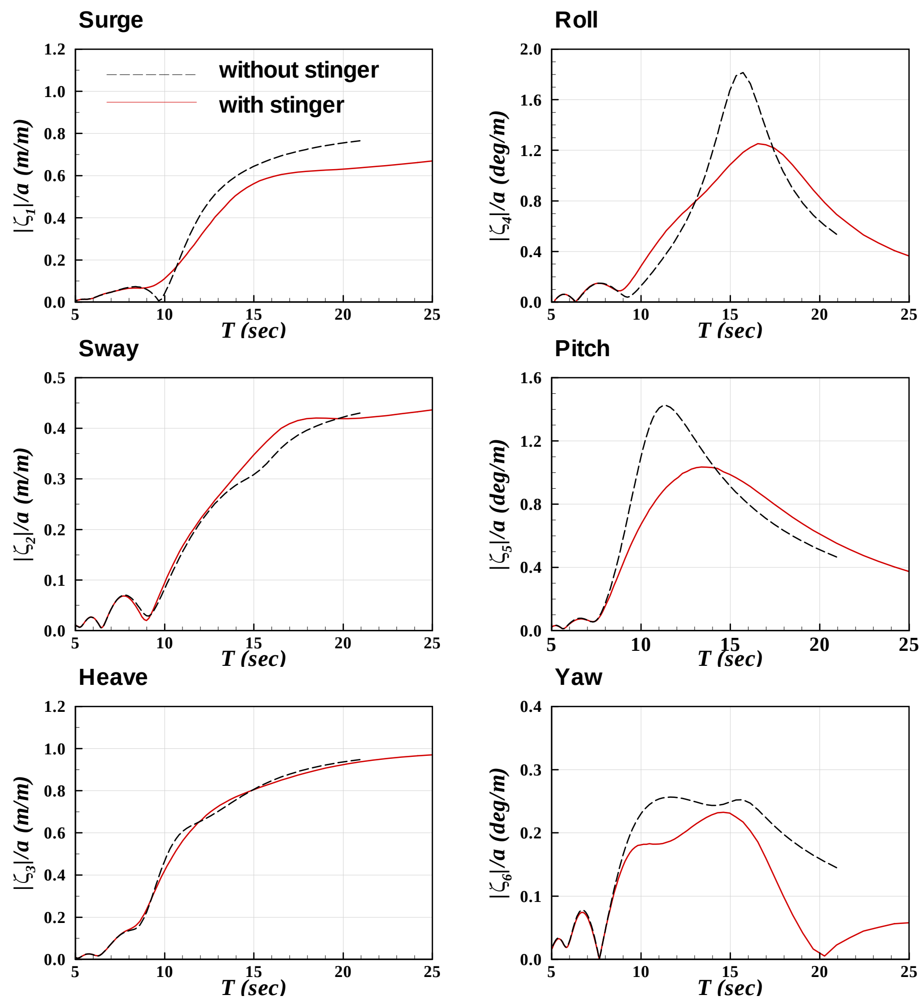

Figure 3. Motion RAO of the pipelaying vessel at zero forward speed and 150 degrees of heading

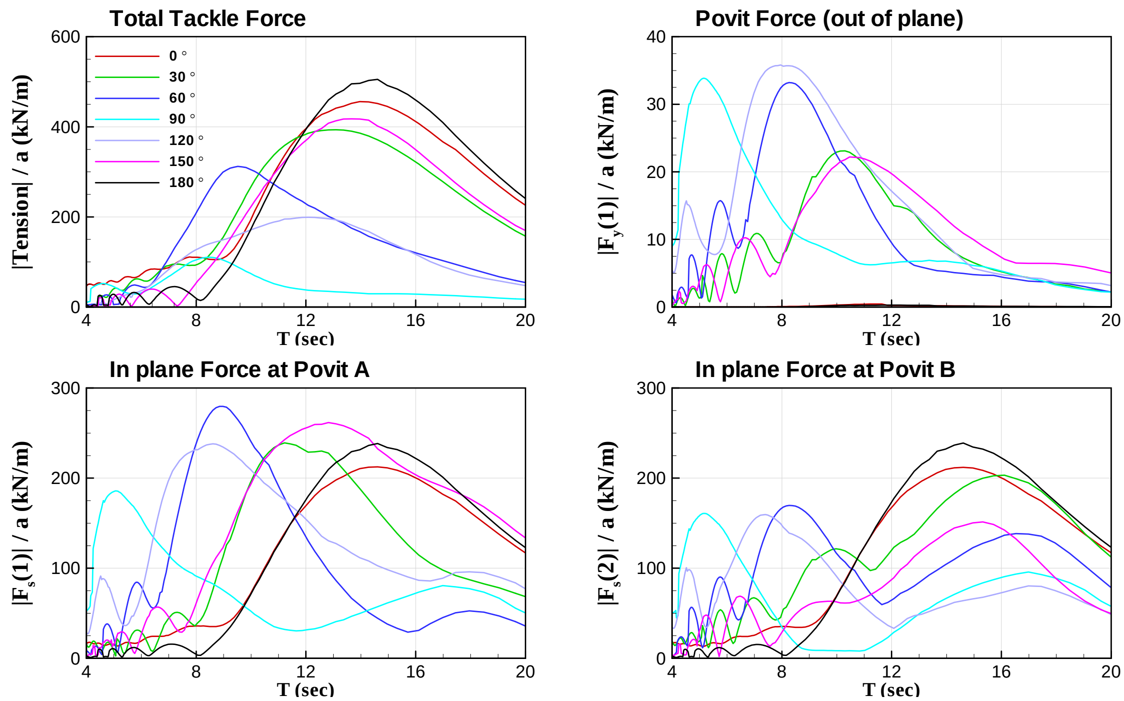

Figure 4. RAO of tackle force and pivot force

The stinger force result has been used to in a short-term statistic computation for a maximum value check. We found from Figure 5 that, in a high sea state where Tp=10 sec., the maximum stinger force based on frequency domain analysis is significantly large than those obtained from a time domain boundary element computation. The reason is that only one seed is used in the time domain analysis due to its long computation time. In general more seeds are required to obtain a reliable time domain simulation.

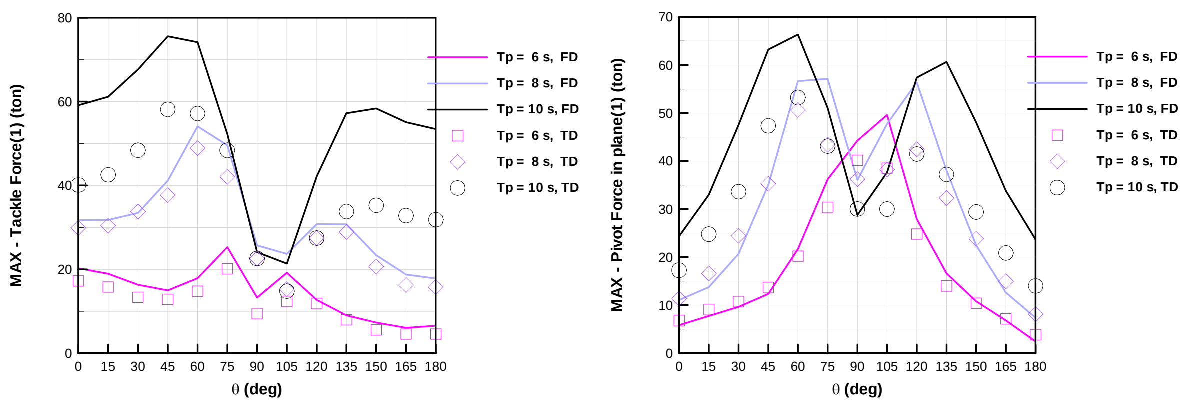

Figure 5. Comparison of 3 hours maximum force by the time domain (TD) and frequency domain (FD) analyses

Tank Sloshing of LNGC/FLNG

The nonlinear viscous flow force has been successfully involved in linear boundary element model in examples of previous section. But we do not always have luck to do so. Sloshing load on wall of partially filled tank is a good example. Structural damage, especially the fatigue one, on the tank

wall is the major threaten for a LNGC and sometimes FLNG. The tank wall damage is induced by the sloshing load due to the liquid flow inside the tank. A large LNGC can have a length of 350 meters; one large LNG tank can be 80,000 cubic meters. For this scale of the vessel and tank, a full ship CFD model, including both fluid domain around the ship and liquid domain inside tanks, will be out of consideration. Instead of that, a combined frequency domain boundary element model and CFD tank model will be selected. In the sloshing coupled boundary element model, an individual tank boundary element model will be adopted to solve the so-called radiation problem of the liquid flow inside a tank. This solution is still the velocity potential one exclude the non-linear flow effect. Adding those added-mass and damping from each partially filled tank in ship motion equation, the sloshing coupled ship motion can be solved. A model of a LNGC with two partially filled tanks is shown on left of Figure 6; the roll motion RAO at zero ship speed in beam seas from an analysis with and without tank flow effect is shown in the right of the figure. The ship motion is totally different when effect of liquid flow in the two tanks is involved; the roll motion from the sloshing coupled model has two peaks instead of one. In Figure 7, other two lateral motions, sway and yaw, in the same condition are presented. The filling ratio is 50% in both tanks. Red lines with name “FDWL” is the results obtained by WAVELOAD-FD, the sloshing coupled BEM model in frequency domain; and the blue marks are the experimental results. The RAO of lateral and vertical total force on the fore tank of the model are presented in Figure 8. The numerical results of the forces correlate with experiments well. These example shows that the inviscid linear BEM model works well for the global responses, ship motion and total tank force. But this model has a time harmonic tank wall pressure prediction and cannot predict the sloshing pressure peaks in a reliable accuracy. A CFD model is then required. An OpenFOAM based tank sloshing CFD tool, Aquarius, has been developed in Global Technology Center of Lloyd’s Register in Southampton. The sloshing coupled ship motion will be computed first by WAVELOAD-FD, and the resultant ship motion will be used to drive the CFD tank model to simulate the pressure distribution due to the sloshing. In Figure 9, a 3D and 2D flow pattern obtained by Aquarius are presented, and pressure time history at different tank wall locations are plotted in Figure 10. The sharp peak of the pressure due to sloshing has been well captured.
This gives an example of using different level of numerical models in one hydrodynamic assessment for industry application.

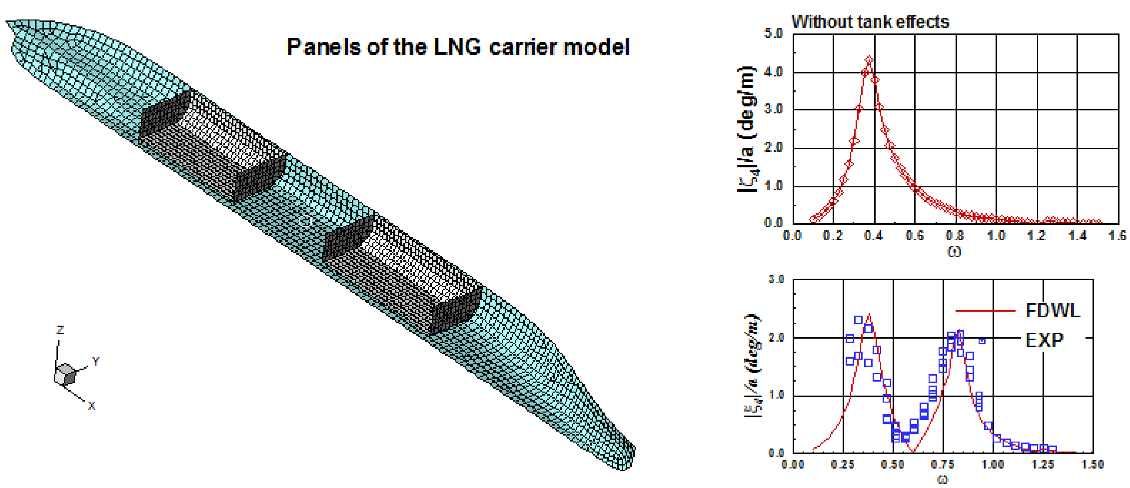

Figure 6. Model of a LNGC with two tanks (top left) and roll RAO without (top right) and with tank flow coupling (bottom right); at zero forward speed in beam sea.

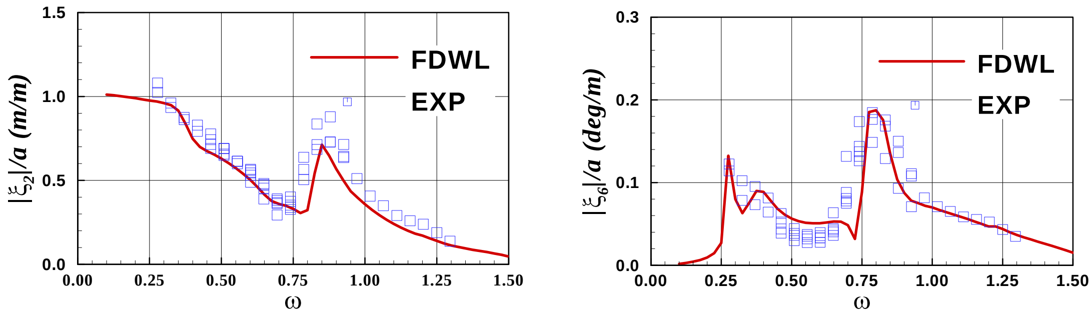

Figure 7. Sloshing coupled motion: sway (left) and yaw (right) at zero forward speed in beam seas.

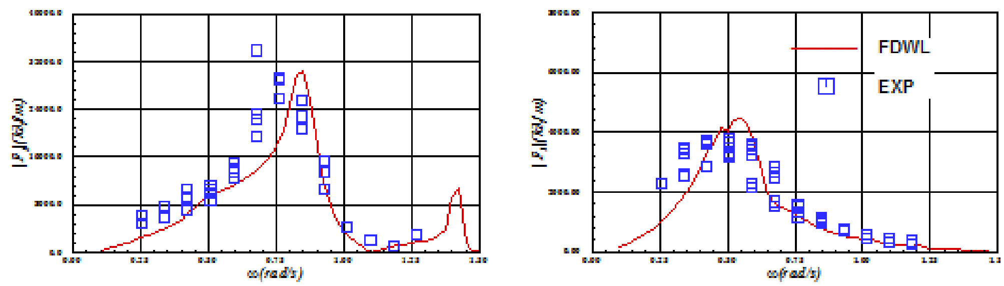

Figure 8. RAO of total tank force: lateral (left) and vertical (right) at zero speed in beam sea.

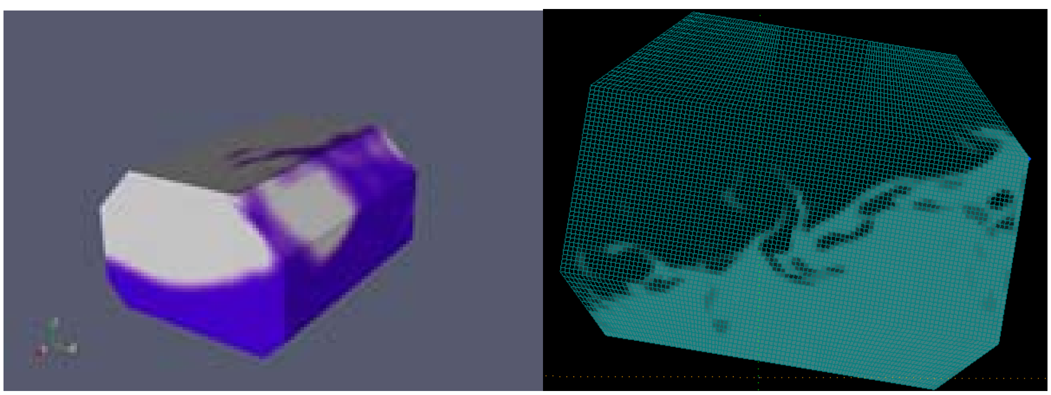

Figure 9. Flow by Aquarius CFD tank model

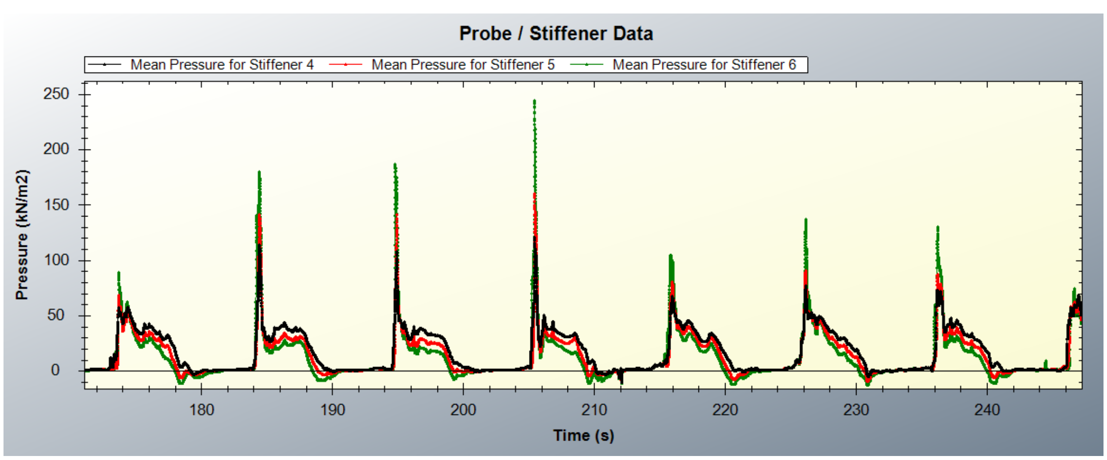

Figure 10. Time history of pressures at specific locations on tank wall by Aquarius

Multi-level Time Domain Approaches for Nonlinear Load Analysis

Frequency domain BEM model has the best efficiency and is used as the main analysis tool in the industry so far. But the linear character of this model has the limitation of its application for small wave and small ship motion. Vertical bending moment and shearing force are used as the typical load in many design and design appraisal works. The critical bending moment and shearing force are estimated from analyses in large wave conditions. Linear BEM model has a basic assumption that there is no vertical geometry change of hull surface around water line, therefore the bending moment in hogging and sagging condition has same amplitude by linear BEM model. On the other hand, hull geometry does change along vertical at least at bow and stern part. As a result, the amplitude of bending moment in hogging and sagging condition is different in large wave conditions. The time domain model based on database of frequency domain analysis is in general required for critical load assessment. As explained in the stinger force analysis, a reliable time domain simulation in a high sea state needs a large number of seeds, which could be as large as 20 for some cases. The multi-seed time domain analysis may then be too time consuming and becomes unrealistic. A simplified time domain approach, so called intermittent, has been proposed by Lloyd's Register. In an intermittent model, ship motion will be kept the same to those obtained by a frequency domain model, and the frequency domain results of ship motion and pressure are transferred to time domain for a specific regular wave condition or sea state, hydrodynamic pressure on hull surface is then been corrected at each time step. By intermittent correction, non-zero pressure will be added on the mean dry hull surface if it is under water surface at that time according to the ship position and the height of total waves. Correction will also be applied on mean wetted hull surface to make the total pressure being zero if that part of hull moves out of water at the time. The corrected hydrodynamic response will be used to compute the loads, bending moment and shearing force. An analysis in a 24.1 meters wave height regular wave condition is presented in Figure 10 through 12. Pressure distribution by the linear BEM model at a time of hogging condition is plotted on left of Figure 10, the one with intermittent correction is plotted on the right. The linear BEM model has negative total pressure around bow and has zero pressure above the waterline. On the other hand, the intermittent model does not have negative pressure and has non-zero pressure above the water line around the middle ship. The pressure around bow has significant contribution to vertical wave making bending moment (VWBM), while pressure on vertical hull surface will have no contribution to VWBM. As a result, the linear BEM model will over-estimate VWBM due to the negative pressure and its VWBM result would be larger than that by intermittent model.

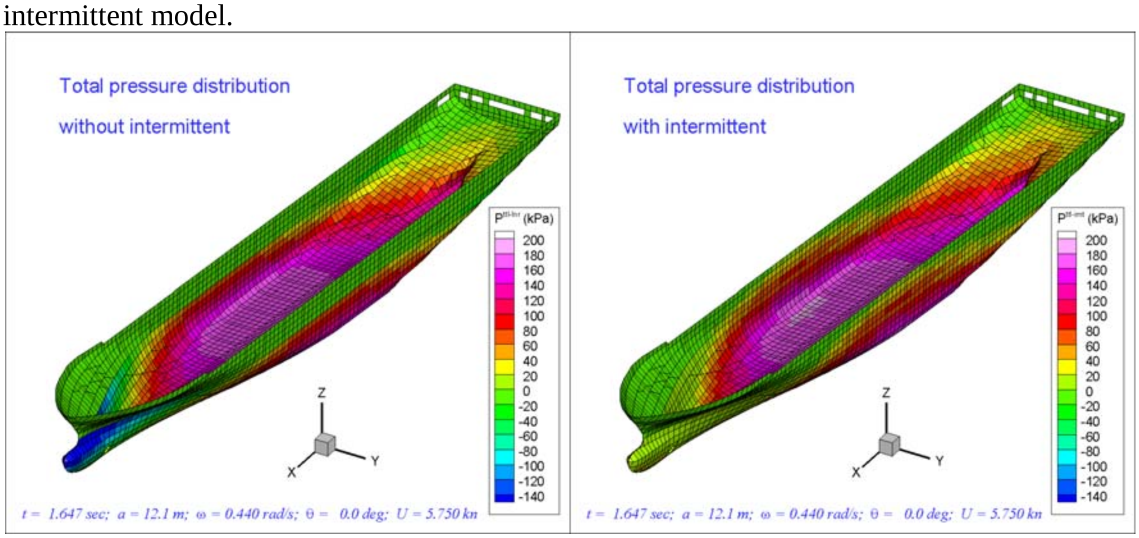

Figure 10. Pressure distribution of linear model and intermittent model in a hogging condition

Figure 11 shows the pressure distribution of the same vessel in same waves but at a time of sagging condition. At this time the linear BEM model has a portion of negative pressure are on vertical hull surface around middle ship area, but the intermittent model got more pressure on bow and stern above the waterline. An increase of VWBM can be expected in the results of intermittent model.

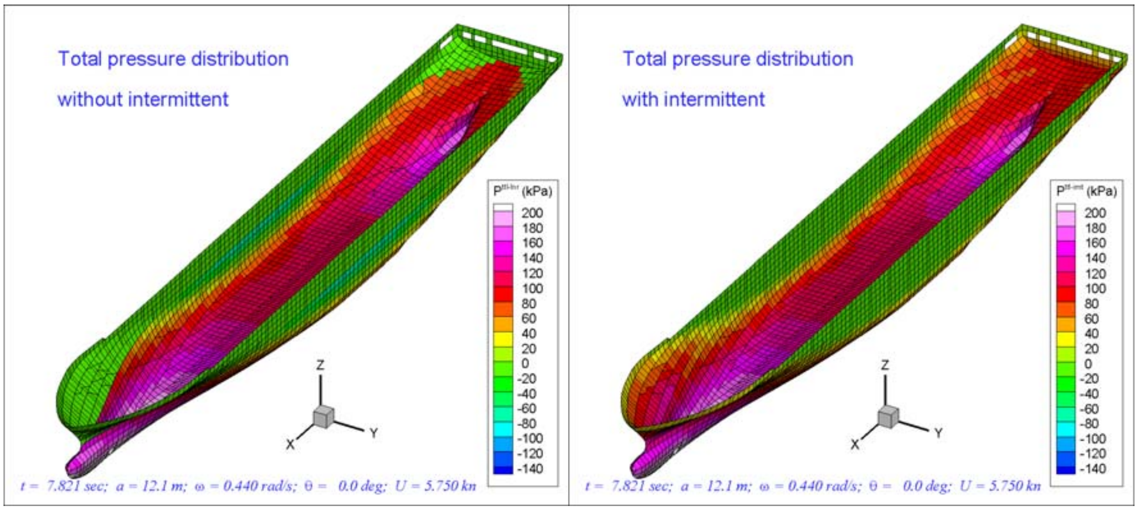

Figure 11. Pressure distribution of linear model and intermittent model in a sagging condition

The longitudinal distribution of VWBM for hogging and sagging conditions obtained by the linear BEM model and nonlinear intermittent model are presented in Figure 12. The results of linear VEM model are in the colour of green, results of intermittent model in colour of black, and the correction part from the intermittent are in red. The hogging results are presented by lines with marks and sagging ones by lines only. The linear BEM model shows a symmetric hogging/sagging result, and results of intermittent model are not. As we expected, intermittent model has a smaller VWBM in hogging, up to 15% on some locations; while for sagging condition, intermittent model got a maximum VWBM around 75% larger than that by the linear model for this extreme high wave

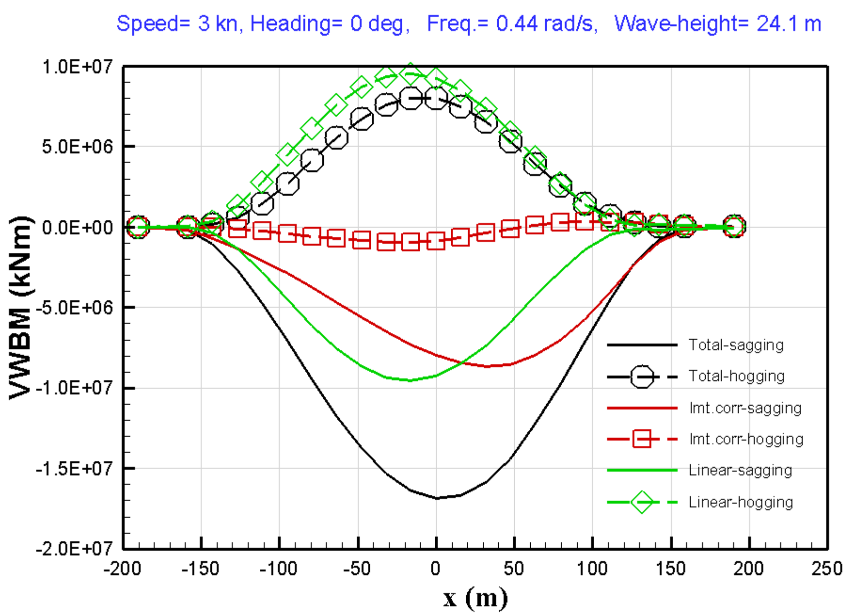

Figure 12. Longitudinal distribution of VWBM in a large wave condition

condition, H=24.1 meters. The VWBM results obtained by intermittent model is closer to the experiments and sea trail data, and could provide a reference load for design and design appraisal. Comparing to time domain BEM model, computation time by an intermittent model is ignorable.

Conclusions

Applications of different approaches based on linear boundary element method and other nonlinear models like CFD, viscous Morrison force and viscous damping, are presented in this work. A simplified nonlinear time domain correction method, intermittent, for design bending moment and shearing force has also been presented. Through these examples, we can see the efforts for improving the efficient numerical tool to answer the requirement from the marine and offshore industry.

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