Proceedings of the ASME 27th International Conference on Offshore Mechanics and Arctic Engineering
OMAE2008
June 15-20, 2008, Estoril, Portugal

OMAE2008-57853

ACHIEVEMENTS IN APPLICATIONS OF MARINE HYDRODYNAMICS

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ABSTRACT

The paper gives a review of the achievements in the applications of marine hydrodynamics to problems in offshore and maritime engineering. In particular focus will be on numerical methods for analysis of ships and floating production systems and how the work of Professor Newman has influenced the development of computational tools for use by the industry.

The paper also presents some recent applications of such numerical tools for analysis of fixed and floating production systems, seakeeping of ships with forward speed including problems related to sloshing and moonpool dynamics. The challenges for each of these applications will be discussed from a physical viewpoint and how the numerical tools are applied to solve the problems. Validation of computer tools in light of their intrinsic limitations will be discussed.

Finally the paper presents some of the most important engineering challenges today with respect to modelling and simulation of loads and response of ships and floating production systems.

INTRODUCTION

Within Det Norske Veritas (DNV) implementation and use of radiation-diffraction programs started in the early 1970s with the development of computer program for prediction of wave forces on large volume structures of arbitrary form, refs. [1], [2]. A typical example of early use of such program including calibration with model tests is given in ref. [11]. At the time computational capabilities were limited which is reflected in the number of panels used in the geometry models. E.g. for the floating box shaped barge (90x90x40m) in ref. [11] the number of elements ranged from 48 to 108, which implied an average diagonal length of 13 – 20m. Typical for this period, i.e. mid 70s to mid/late 80s was a continuous evaluation of how large and detailed models could be made and how low wave periods could be analysed. At the time there was also high focus on gravity based structures (GBS) in the North Sea and radiation-diffraction analyses were essential for detailed design. This applied to global wave loads as well as peculiar effects like the caisson effect (local increase in wave elevation due to the large caisson) and off-body kinematics, i.e. increased wave and current particle velocities due to the presence of a GBS on a jacket or jack-up in close proximity.

For moored floating objects, the introduction of Newman's approximation [13] for 2nd order slowly varying forces on vessels in irregular sea was a major step for the industry. Some claim that 'the position of this approximation in the industry has been so firm that sometimes it is hard to convince people that it really is an approximation' [22]. Within DNV, as for the rest of the industry, numerous analyses using this approximation have been performed during the last thirty years. This approximation together with efficient Green function calculations and the possibility to analyze wave radiation and diffraction for large and complex geometries both to first and second order are key achievements by Newman.

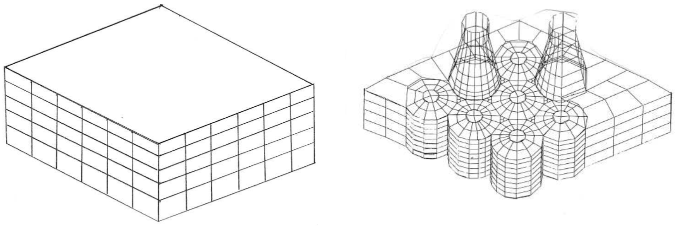

Figure 1 Floating barge (1976) and Gravity Based Structure (quarter model; offbody kinematics) (1984)

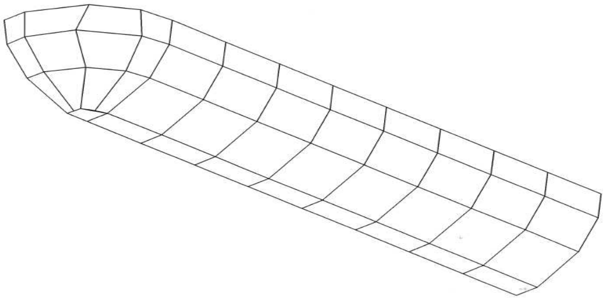

Figure 2 Floating Bridge Pontoon (quarter model) (1988)

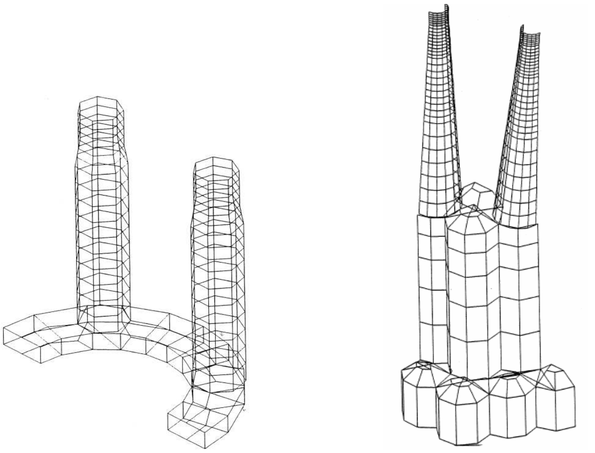

Figure 3 Deep Draft Floater (half model) (1986) and Deepwater GBS (half model) (1989)

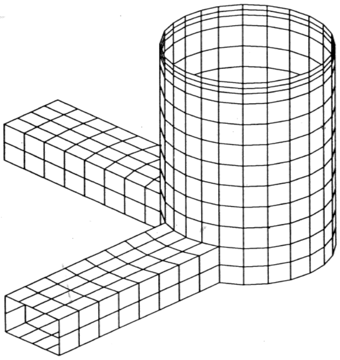

Figure 4 Tension Leg Platform (quarter model) (1993)

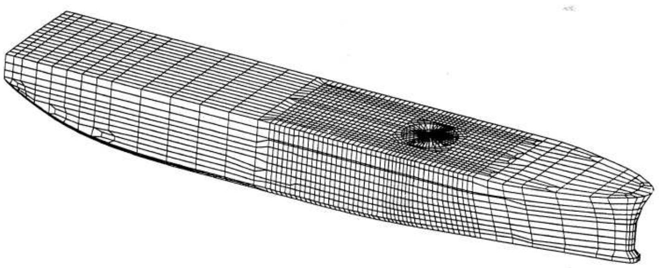

Figure 5 FPSO with turret (1994)

The development of very efficient algorithms for calculation of free surface Green functions in the mid 80s [14] and their implementation in a new generation radiation/diffraction computer program through the release of the first version of WAMIT [25] in 1987 was also a major step forward. There is probably no other computer code that has been equally important with respect to analysis of waves interacting with offshore floating structures. DNV played a key role in the initial development of WAMIT as an industrial tool. In fact DNV proposed a specification of the design and user requirements for such a computer tool. This served as the basis for the development of the first version. Within DNV's SESAM suite of computer programs, WAMIT was used as the numerical calculation engine in the general wave load prediction program named WADAM [24]. Potential flow radiation and diffraction pressure loads on large volume structure are combined with viscous Morison type loads on slender structures and hydrodynamic loads are automatically transferred to FEM programs for subsequent structural analysis. This program is widely used by DNV and in the offshore industry both for offshore applications (fixed and floating structures) as well as within the maritime industry for ship shaped structures.

The figures presented in this paper provide an overview of some of the radiation-diffraction geometry models used in DNV projects over the last 3 decades. The figures show both fixed platforms and floating offshore structures as well as coastal structures like the pontoons for floating bridges. The figures also show the refinements and complexity in analyses when including surface mesh for higher order wave loads. The development of fast algorithms and the continuous improvement of computational power has made accurate predicitions of complex wave structure interaction problems for floating bodies feasible. This includes analysis of multiple floating bodies, side-by-side vessels with narrow gap, floaters in restricted and/or shallow water, very large (relative to wavelength) floating concepts.

Fixed Stationary Structures

The start-up of the offshore industry in the North Sea in the late 60s and early 70s resulted in a need for analysis tools to estimate wave loads on large gravity based structures (GBS). Diffraction analysis programs became available and in combination with model testing it was possible to estimate global wave loads. Some special purpose programs were established in order to estimate global wave loads as well as dynamics in e.g. shafts. Global wave loads on the caisson was determined from tabulated empirical/test data. Drag loading on shafts was included via the Morison equation with wave length dependent inertia coefficients according to the McCamy Fuchs theory. Typical concrete GBSs are shown in Fig. 10. Some of the most important aspects for GBSs with respect to wave loading and response are discussed briefly.

Total global wave loading is governed by the size of the caisson (oil storage cells). An important feature of the large caisson is the reduction in global overturning moment due to the hydrodynamic pressure acting on the caisson roof. This has great importance with respect to available soil capacity. With skirts below the caissons the hydrodynamic analyses usually did not take into account any wave pressure penetrating through the soil, however the hydrodynamic wave pressure at the caisson perimeter was taken into account in geotechnical design.

For GBSs in relatively shallow water (80 – 150 m water depth) the dynamic amplification is small and the first global bending modes have eigenperiods less than 2 seconds. Still dynamic analyses were performed to determine the dynamic amplifications (DAFs) for global wave loads as well as shaft moments. Typically the DAFs were in the range 2 – 15% and highest for bending moments at top of shafts. For the largest GBSs in deeper waters, i.e. around 250 – 350 m the fundamental eigenperiods are higher and higher DAFs will have to be taken into account in design.

Typical diameters of the shafts imply that the response is inertia dominated. However it became common practice to combine drag and inertia from Morison equation using the McCamy& Fuchs inertia coefficients (as function of shaft diameter/wave length). One important consideration here is that in a standard linear diffraction analyses pressure loads are only integrated up to the still water level. In the case of relatively slim shafts it was found necessary to include drag loads integrated up to the instantaneous free surface elevation.

The term “caisson effect” was used for these GBSs. Due to the presence of the large caissons the wave elevation was influenced and this was typically taken into account when determining the air gap. An additonal air gap of 1.5m was included in design for all the initial GBSs built in the North Sea. For large/wide GBSs in relatively shallow water in combination with extreme waves (e.g. waves with return period of 10 000 year) caution has to be shown when using linear diffraction analyses as the small distance from caisson roof to still water level may lead to wave breaking. A linear analysis overestimates the wave amplitude directly above the caisson. Model tests may be needed for such situations.

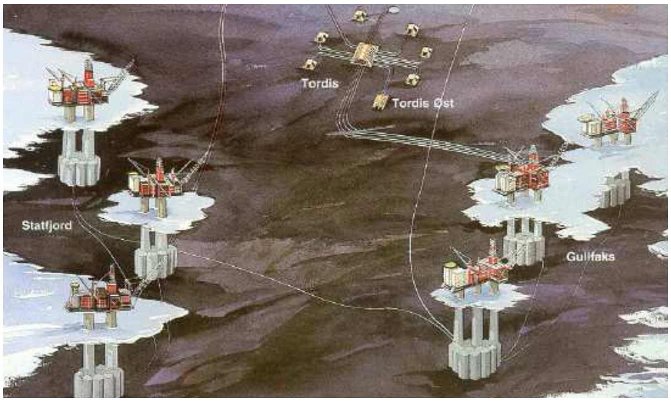

Figure 6 Gravity Based Structures, North Sea

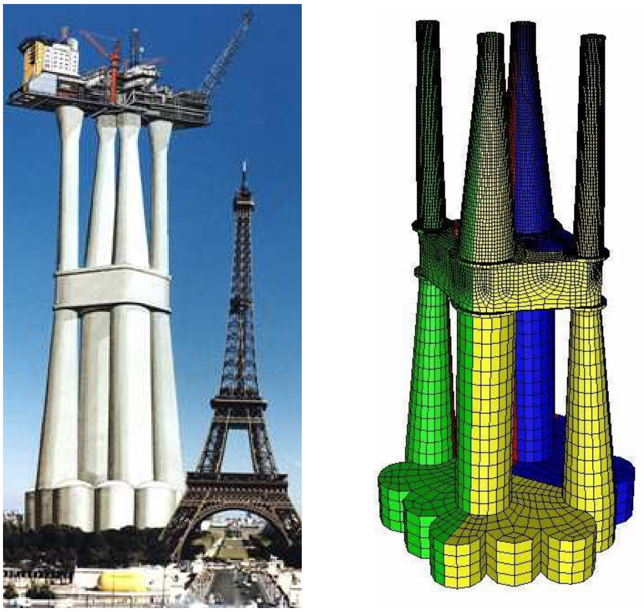

Figure 7 Troll A GBS. Artist impression of size relative to Eiffel tower. Panel mesh for 2nd order load calculation (2007).

The term “offbody kinematics” also came into use as a result of available diffraction programs that could assess the effect of large volume structures on wave particle kinematics in the vicinity of the structure. This could e.g. be in relation to determining the increase in particle velocity and acceleration for risers routed along the caisson and up along the shaft. The change in flow and direction due to the presence of the GBS is significant and a lot of wave headings and periods had to be taken into account for design of e.g. a clamped riser. Diffraction analyses were also highly valuable when assessing loads on e.g. jackets or jack-ups placed close to a large volume structure. Also for the influence from structures on current flow, diffraction programs have been used by defining an incoming wave with very long wave lengths. Linear potential theory fails to predict e.g. local run-up close to a shaft, however in combination with experiences from model testing it is possible to make some use of diffraction analyses, also for this local problem.

For fixed platforms/GBSs in deeper water, say 250 – 350m, the fundamental eigenperiods will increase to around 4 – 5 seconds and dynamic effects become more important. The classical first order diffraction analyses for response in six-degrees of freedom were extended to include flexible mode analysis [16]. In deep water the positive counter-wave effect on the overturning moment is almost gone and global soil stability is a key issue. Due to tie-ins of new fields and resulting increase of topside weights, dynamic effects may become even more important and it may be necessary to consider higher order wave loading. Extreme waves of period *T* may excite resonant springing and ringing response of the GBS if the natural period is close to *T*/2 or *T*/3. Since wave lengths of extreme waves are long compared to the diameter of the GBS shaft, a long wavelength theory was developed for regular waves by Faltinsen, Newman and Vinje (FNV) [3] and extended to irregular waves by Newman [17]. This theory has recently been applied to assess higher order wave loading on the Troll A GBS (Figure 7). Distributed first and second order wave diffraction pressures on each panel are integrated up to still water level and added to a long wavelength approximation for the third order FNV force acting at the free surface. Resulting time series for base shear force and overturning moment compare well with results from model test.

Floating Stationary Structures

There are multiple types of floating offshore structures which have been subject to radiation-diffraction analyses. Two of them are selected here for a more detailed discussion; i.e. Tension Leg Platform (TLP) and the Spar Platform concept.

Figure 9 shows a panel model for a large displacement TLP designed for moderate water depth (350 m) and harsh environment. Radiation-diffraction analyses are crucial for design of many of the components/systems of such platforms; i.e. hull structure, tendons, risers, foundation as well as deck/topside. For a floating body the radiation forces, i.e. added mass and damping force, are an important part of the global loads and must be treated adequately.

Important higher order hydrodynamic load effects for such a TLP include slowdrift motion, high frequency springing and ringing response. These are second and higher order load effects and need to be taken into account by a careful hydrodynamic analysis. Second order difference frequency wave loads are an important part of the excitation of slow drift motion and must be taken into account to determine the maximum horizontal offsets in storm conditions which is crucial for tendon and riser design. An important aspect of TLP slowdrift is the fact that the second order surge and sway forces increase with decreasing wave periods whereas the wave frequency motions decrease. This has a direct impact on resulting offset and implies that a range of peak periods have to be checked to determine the maximum TLP offset.

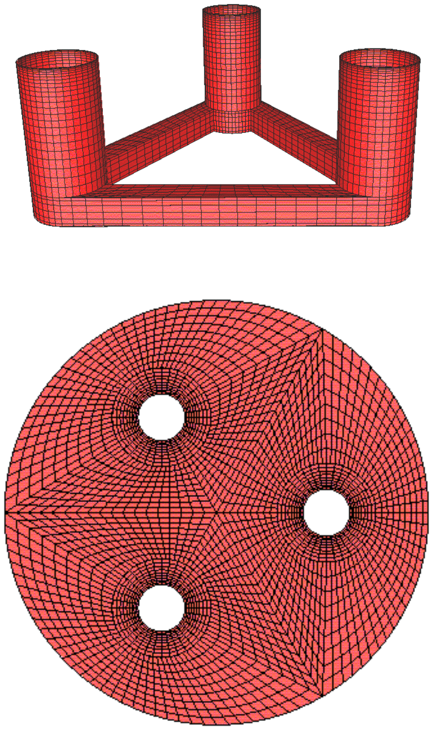

Figure 8 Three-legged TLP. Panel mesh on wetted surface (4968 elements) and free surface (2916 elements) for calculation of wave drift damping.

The slow drift motion of moored floating production systems are limited by hydrodynamic damping forces. In addition to the viscous damping from relative motion between the floater and waves/wind there may be a substantial contribution to damping from wave drift damping which can be modelled by potential flow. Wave drift damping can be defined as the first order correction in terms of the slow drift velocity of the mean wave drift force. Being proportional to velocity this correction term acts as a damping force in the equations of motion. Based on WAMIT a computer code for prediction of the full 3x3 monochromatic wave drift damping matrix for horizontal slow motions was developed by University of Oslo (Ref. [5]). Panel mesh used for calculation of wave drift damping on a three legged TLP is shown in Figure 8.

Vertical sum-frequency response, or tendon springing, is a peculiar TLP effect which has to be analysed with radiation-diffraction programs. Such analyses are time consuming requiring a large number of panels on the wetted surface as well as on the free surface for a large number of combined frequencies (bichromatic). Today such analyses are considered state of the art, but are still challenging for the analyst since careful selection of both panel mesh and wave frequencies is required. In addition there is often great uncertainty with respect to damping level in tendons which is essential for calculating springing response.

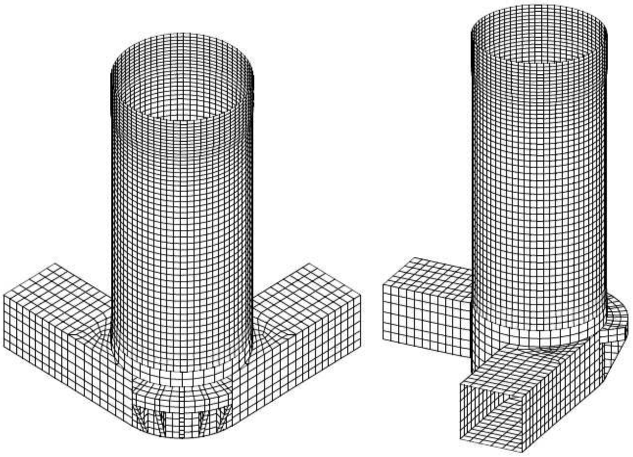

Figure 9 Large TLP. Panel mesh for 2nd order analysis (4500 elements per quadrant)

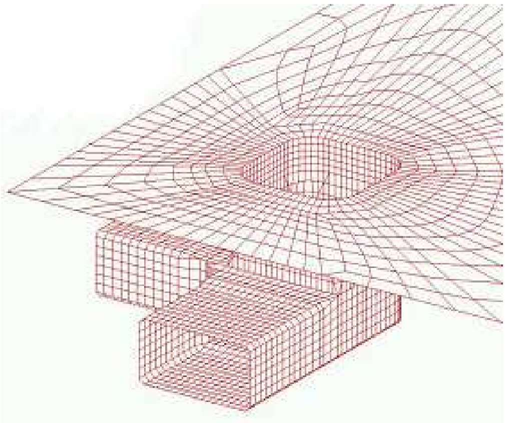

Figure 10 Semisubmersible (quarter model) (2004). Including free surface mesh for 2nd order calculations.

Over the last decade a number of Spar structures have been installed, mostly in Gulf of Mexico and one outside Malaysia. The first 3 Spar units installed were so-called Classic Spars. The newer units have mostly been Truss Spars and a slimmer type named Cell Spar. Common for all these are the relatively large draft and thereby favourable vertical motions to accommodate riser and mooring hang off.

Treating the Classic Spar as closed at keel level implies a simple model for radiation-diffraction analyses. Figure 11 shows an open moonpool model for radiation-diffraction analyses that was carried out by DNV in 1997. This resulted in a considerably larger model and some simplifications had to be introduced by increasing the hull skin thickness to 2 m with panels on each side using a sink-source formulation. Convergences and the influence of strakes on the added mass, yaw excitation and global performance was also tested by modelling the strakes in WAMIT. The complete model consisted of more than 10000 panels.

The Truss Spar (Figure 12) is more challenging with respect to global analyses. This is a hybrid structure with a hard tank, truss structure, heave plates and a soft tank. High eigenperiod in heave is ensured by the horizontal plates in the truss area and the plates also provide additional damping in heave. There are different approaches for simulating global performance of this type of structure. DNV usually makes use of a combined radiation-diffraction and Morison analysis [24]. For the heave plates either modelling both upper and lower part of the plates using sink-source method, or as an infinitely thin plate using dipole distribution can be used. By careful selection, these two approaches will give similar global loads. An issue to be aware of related to the hard tank, is whether to simulate this fully open, or partly/completely closed. Either way, both hydrostatic heave stiffness and heave excitation are influenced by this choice and will have to be considered.

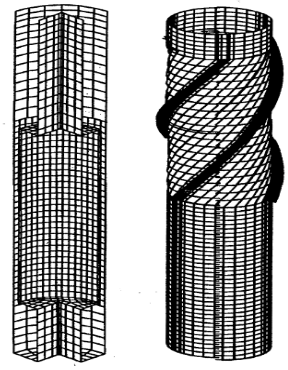

Figure 11 Classic Spar with moonpool and strakes (1997)

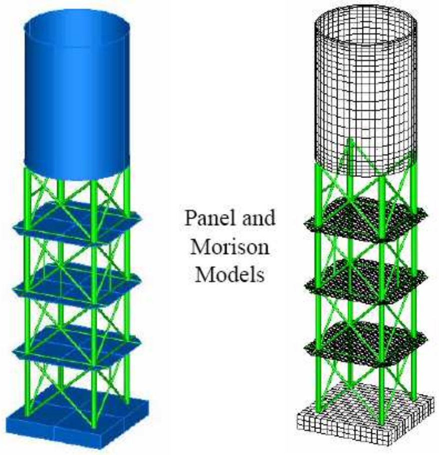

Figure 12 Truss Spar (2001). Composite panel and Morison model.

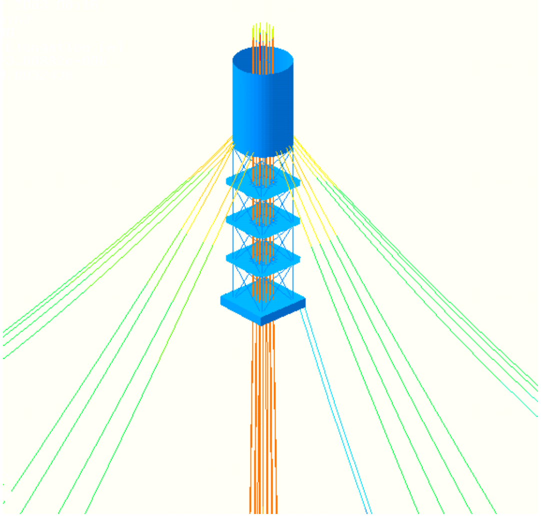

Figure 13 Truss Spar model with mooring lines and risers for coupled analysis.

Coupled analyses may be required for analysing Spar units. In particular this applies for concepts which have special tensioner supported risers. For these, coupled FE analysis with careful simulation of the stick/slip behaviour at tensioner hang off as well as at keel will be required (Figure 13).

SEA-KEEPING OF SHIPS WITH FORWARD SPEED

Direct numerical analysis of wave loads and motions of ships with forward speed is now an everyday task for classification societies. Several computer programs can be used to get accurate estimates of e.g. midship bending moments for monohulls at not too high Froude numbers. The work of Newman ([14], [15]) related to accurate calculation of the free-surface Green function has been extremely important in the development of current numerical tools. At DNV, the most widely used forward speed wave load analysis program is Wasim.

Overview of Wasim

Wasim originates from a co-operation between DNV and MIT starting in 1990 to further develop the computer code Swan for analysis of wave induced response of ships with forward speed. Work had been started at MIT in the late 80s to develop stable schemes for forward speed problems [12]. In the start of the development a lot of effort was put into analyzing different numerical schemes for best possible performance and to get control over the numerical error sources [23]. From 1996 Wasim was developed further by DNV. This development was done in parallel with the use of the program for practical applications in new-building ship activities. Thus the further development has consistently focused on practical applications.

Wasim is based on potential flow theory using a Rankine Panel method, with panels on the hull and free surface. A numerical beach is included on the outskirts of the free surface. The equations are solved in time domain and the solution is fully three-dimensional. An important characteristics of Wasim is the use of B-splines in the representation of the velocity potential and its normal derivative. The general B-splines concept was introduced to the Boundary Element Method (BEM) by Hsin et al. ([7]).

Usually viscous damping is tuned based on empirical methods. The output from Wasim is time histories of the rigid body motion, sectional loads, free surface elevation and pressure distribution on the hull. Facilities for animation of rigid body motion, wave elevation and pressure distribution are also available. Wasim has no theoretical limitation in wave frequency, wave heading or vessel speed, as long as the vessel is not planing. There may be a practical limitation in speed due to the fact that both spatial and temporal discretization must be refined with increasing speed. This is only a problem at very high Froude numbers.

The basic version of Wasim is linear, but there is also a non-linear extension. The idea behind the non-linear extension has been to include the most important non-linear effects without any dramatic impact on the CPU cost. For this reason the radiation/diffraction problem is always solved on the mean wetted hull, but the following effects are handled in an exact manner:

- The Froude-Krylov and hydrostatic pressure is integrated over the exact wetted surface. This means that the vessel is in its instantaneous position and the integration is performed up to the actual waterline. There is an option to use either total wave elevation or the incoming wave.
- The equation of motions is solved in an Eulerian frame.
- The quadratic terms in the Bernoulli equation are included in the computation of the pressure distribution.

The non-linear option also allows for the inclusion of a quadratic roll damping term in addition to the linear damping.
For a linear analysis Wasim offers an option to transfer the results from time domain to frequency domain, giving transfer functions for all the output data listed above.

Special features of Wasim include integration of hull flexible analysis, slamming and green water as well as advanced motion control functionality by means of active or passive stabilizer fins or rudders. Slamming may be included by running a pre-processor calculating slamming loads on a set of two-dimensional strips of the hull using a generalized Wagner's method. The slamming coefficients and potential flow solution are extracted from the slamming database and the pressure is calculated and mapped on the panel method. A proper time averaging procedure is applied in order to account for slamming. Simulation of green water on deck is based on predictions of dam break type shallow water flow combined with a Random Choice Method for solution of the hyperbolic shallow water equations (Glimm's method).

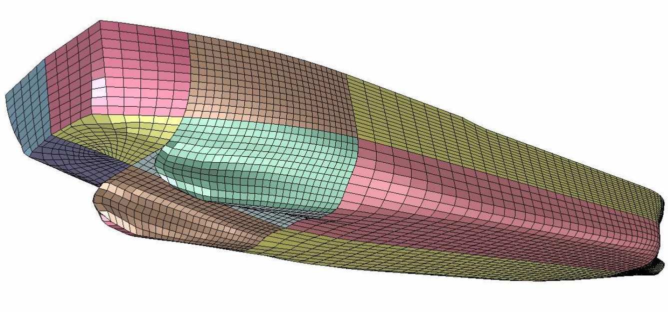

Figure 14 Wasim panel model of a twin skeg LNG carrier.

Typical application of Wasim

A typical application of Wasim would be to assess ultimate limit state (ULS) hull girder loads. The ship hull is discretized by quadrilateral panels, both the wet and dry part. Figure 14 shows a typical panel model of a twin skeg LNG carrier. Linear simulations and the Coefficient-of-contribution method are used to identify the critical sea-state in the relevant scatter diagram. A nonlinear factor on the hogging- and sagging moment is established based on nonlinear Wasim calculations, either from simulations in irregular waves in the critical sea-state, or from a conditioned irregular wave (Most Likely Extreme Response, MLER) approach. If relative motions indicate that slamming or green water loads may be important, these effects can be accounted for. The calculation procedures to determine extreme responses of ocean-going structures using nonlinear time-domain simulations were presented by Pastoor et.al. [20].

ENGINEERING CHALLENGES IN WAVE LOAD ANALYSIS

The following discussion focuses on potential flow solvers based on boundary element methods. More general computational fluid dynamics tools, i.e. field solvers combined with a surface-tracking method like Volume of Fluids are now becoming useful when strongly nonlinear transient events are being studied. However, boundary element methods will probably be the primary tool in wave load analyses for many years to come.

BEM has been recognized as an accurate and efficient method for predicting local flow characteristics as long as the actual fluid boundary is handled properly. The efficiency of BEM is mainly due to the relative small number of elements required, compared to field solvers, combined with accelerated $O(n \ln n)$ or $O(n)$ influence calculations like pre-conditioned FFT and Fast-Multipole-Methods.

When analyzing ship motions in severe sea-states the wetted body surface may change considerable with time resulting in a need for automatic and temporal boundary modeling. High robustness and efficiency of such algorithms is a prerequisite for this type of calculations. The spatial discretization must be adapted to significant instant flow gradients. Sharp surface gradients must be modeled in case of important physics like the steep “ringing”-wave behind a vertical cylinder or a slamming impact. Sharp but unimportant gradients, like formation of foams of small breaking waves, should not be modeled in order to save computational efforts. Hence efficient and robust algorithms needs to be developed that can distinguish important and unimportant gradients.

Robust methods for tracking the intersection line between the free-surface and body surface is particular challenging in case of flared bodies. Flow separation from two-dimensional bodies has been studied by several authors but general methods for double-curved three-dimensional surfaces need to be developed. Assuming a robust automatic geometry modeller is at hand, the main obstacle for BEM is to simulate beyond the point of breaking waves and handling of important viscous effects related to e.g. roll damping. The latter effect has traditionally been accounted for by heuristic and empirical coefficients. Discrete vortex distributions combined with a classical boundary element method has been successfully applied for 2D roll problems [26] and promising methods for 3D wake modelling are being investigated. Newman [18] discusses the use of a viscous post-processor to potential solutions, see Graham et al. [6].

It is expected that many important responses can be investigated by applying an adequate Fourier decomposition of the ambient wave flow assuming Airy wave theory. However nonlinear incident wave models may be important for extreme responses in a situation where the ship encounters a freak wave.

Typically the fatigue loading and extreme response of a ship are determined based on standardized long-term distributions of sea-states, e.g. the IACS North-Atlantic scatter diagram. The sea-states are represented by mathematical wave spectra like Pierson-Moskowitz or JONSWAP. These simplifications may cause inaccuracies. New wave data based on satellite measurements are not consistent with established statistics from ship reports. A ship will use routing to avoid the most severe weather conditions. Climate changes may cause more heavy weather. Thus, there is a need to develop better wave statistics and to further develop the wave load analysis calculation procedures to reflect ship operation.

Coupling between ship motions and sloshing is relevant for Liquid Natural Gas (LNG) carriers operating with partially filled tanks. WAMIT has been extended to include the effect of coupling with linear sloshing, see Newman [16] and Kim [9]. Rognebakke and Faltinsen [21] discuss this coupling effect. A straightforward method to account for coupling effects is to use an impulse response function method to solve the linear ship motions while the nonlinear sloshing flow is modeled by a multimodal method [4]. Efficient calculation of impulse response functions for calculation of ship motions in the time domain is discussed [10]. A special treatment is presented, which minimizes the truncation error.

FPSOs, drilling units and some offshore supply vessels have moonpools that may need to be considered in a wave load analysis. A reasonably accurate estimate of dynamic pressures inside the moonpool may be important for a fatigue assessment. A straightforward modeling of the moonpool with submerged walls and free surface may cause problems when using linear BEM. The solution blows up for incoming waves with frequencies close to the resonance frequencies for standing waves in the moonpool. Newman [18] has shown how the standing wave motion in the moonpool around resonance can be treated by introducing massless lids with specified damping in order to limit the resonant amplitude. The lid damping represents the actual dissipation of the standing waves due to viscous effects and separation. Tuning of the damping effect needs to be done by comparison with experiments.

CONCLUSION

The objective of this paper has been to review major achievements in the development and application of marine hydrodynamics to engineering challenges in offshore and maritime engineering. It is shown that the field of marine hydrodynamics has undergone tremendous development since the early 1970s strongly influenced by the works of Prof. Newman. The theoretical developments have been taken into use by industry and have eventually influenced critical engineering practices and enabled the design, construction and operation of a large number of offshore and maritime structures.

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