Non-linear Motion and Wave Load Analysis for Floating Structure Design

Pan Zhiyuan[1] Vada Torgeir[2] and Zhang Zhiping[3]

[1]House No. 9, 1591 Hong Qiao Road, Hong Qiao State Guest Hotel, Shanghai, China, 200336
E-mail: **Peter.Pan@dnv.com**

[2] DNV Software, Høvik, Norway, NO-1322
E-mail: **Torgeir.Vada@dnv.com**

[3]House No. 9, 1591 Hong Qiao Road, Hong Qiao State Guest Hotel, Shanghai, China, 200336
E-mail: **Zhi.Ping.Stone.Zhang@dnv.com**

Abstract

Wasim has become a well established tool for a variety of different analyses of ships and offshore floaters. A brief description of Wasim is given in this paper. We will demonstrate the usability of the Wasim for different analysis types, including sea-keeping analysis, load transfer of linear wave loads for FLS analysis and determination of sea state for ULS analysis. Particular focus will be put on how the non-linear feature of Wasim is taken use.

Keywords: Motion; Wave load; ULS; FLS

Introduction

Wasim originates from a co-operation between DNV and MIT. 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 (see Vada & Nakos [1]). Since 1996 Wasim has been developed further by DNV, and has been fully interfaced with the other programs in the SESAM system. This development has gone hand in hand with the use of the program in practical consulting work. Thus the development has consistently been focussing on practical applications.

Wasim is based on potential theory using a Rankine Panel method. The equations are solved in time domain and the solution is fully three-dimensional. Output from Wasim are 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 as an interface file to SESAM post-processing tool, Xtract.

Wasim has no theoretical limitation in vessel speed (as long as the vessel is not planing), wave frequency or wave heading. 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 should however only be a problem at very high Froude numbers.

The basic version of Wasim uses linear theory, but there is also a non-linear extension. The idea behind the non-linear version has been to include the most important non-linear effects without 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 exactly:

- 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.
- Finite rotation angles are used in inertia and gravity terms.
- 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 by means of FFT, giving transfer functions for all the output data listed above. This means that transfer functions may be post processed using standard SESAM tools (Postresp) for combining the transfer function with relevant sea states and performing standard linear statistical analysis.

Even more important is the automatic transfer of loads from Wasim to the FEM solver Sestra. Wasim will produce output files with inertia and pressure loads that may be used directly as input files to the FEM solver. There are two different options for transferring loads: frequency domain loads or load snapshots at selected points in time.

With both options the loads that are transferred are the following:

- Inertia loads in the form of the six rigid body acceleration components
- Pressure distribution on the hull
- Pressure in tanks from internal fluid

The pressure due to internal fluid is computed based on the simplified assumption that the fluid in the tanks moves as a rigid body. Then the isobars will be given from the combination of the acceleration of the fluid and the acceleration of gravity.

Wasim was initialized as a computation tool for ships. However, with the more general and flexible geometry modelling and meshing, it is possible to be taken use for offshore floaters, such as Spar, TLP and Semi-submersibles, especially under those condition where nonlinearity or current speed effect may not be omitted.

1 Sea-keeping

Sea-keeping problem has been well treated with frequency domain solvers like Waveship which is based on Strip theory and is capable to deal with moderate forward speed problem for ships, and Wadam which is a zero speed 3D solver for offshore floaters and has been extended to cope with 2nd order problem. However, the solutions by both solvers, among others, are found with wet hull up to the mean free surface, so that non-linear effects of the changing geometry around the waterline can not be tracked. Due to the fact that the main part of such nonlinearity is from the Froude-Krylov and hydrostatic forces, Wasim is capable to capture the nonlinear phenomena despite that the radiation/diffraction solution is still linear. In the following, two challenging tasks are assigned to Wasim to testify its ability to cope with sea-keeping instability problems.

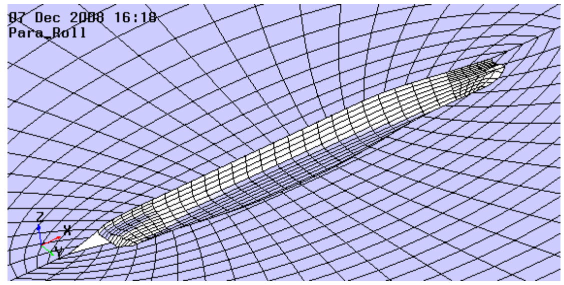

Figure 1: The computational mesh of the containership.

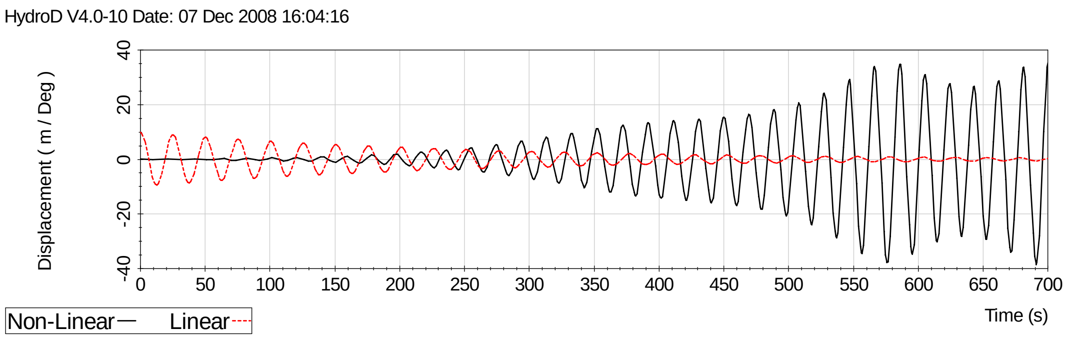

Figure 2: A comparison of the roll motion time series as computed by Wasim nonlinear option (full line) and by linear option (dash line) for a containership in head sea. An initial roll displacement 10 degree is assigned for the linear calculation..

Waterline Length [m]	288.5 / 284.8
Breadth centre hull on waterline [m]	32.2
Displacement [m^3]	9.627E+04
Draught centre hull [m]	15.48
Roll Metacentric height / KG [m]	0.863 /14.23
Roll radius of gyration [m]	11.12
Rolling period [s]	25.6
Forward speed [m/s]	2.55
Wave period/height [s / m]	11 / 12
Critical roll damping	0.02

Table 1: Table 1: Main particulars of the containership

First, both linear and nonlinear calculations are carried out for a containership in head sea to test if parametric rolling can be captured. The main particulars, the meshing of the ship and the time series of roll motion are shown in Tab. 1 Fig. 1 and Fig. 2. The incoming regular wave is selected such that the encounter wave period is approximately the half of the rolling period. It is shown in Fig. 2 that with linear option, the roll motion is damped out whereas the large amplitude parametric rolling is developed in nonlinear solution as expected.

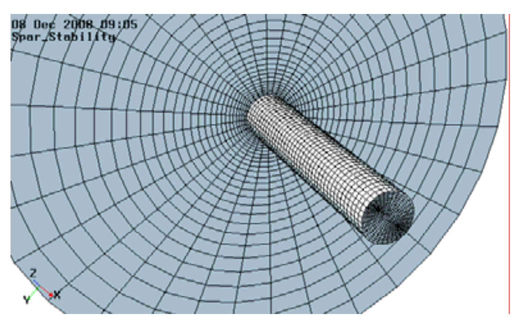

Figure 3: The computational mesh of the Spar buoy.

Parametric rolling is believed to be controlled by the Mathieu equation. It tends to occur when, the relative value of the period of the spring-stiffness variation (with large enough amplitude) to the natural period of the system equal to 1/2, 1, 3/2…. Spar buoy is another type of floater tends to suffer such instability. A spar with particulars as following is selected for Wasim analysis: diameter = 37.5; draft = 202.6 m; wave period = 22.6 s; natural pitch period = 86.5s; natural heave period = 29.3s; KG = 92m; radius of gravity Rx=59.67. The computational mesh is shown in Figure 3. Figure 4 shows the time series of the heave/pitch motion in regular incoming wave. The linear solution is shown as periodic whereas the nonlinear solution shows a developing instability of the system.

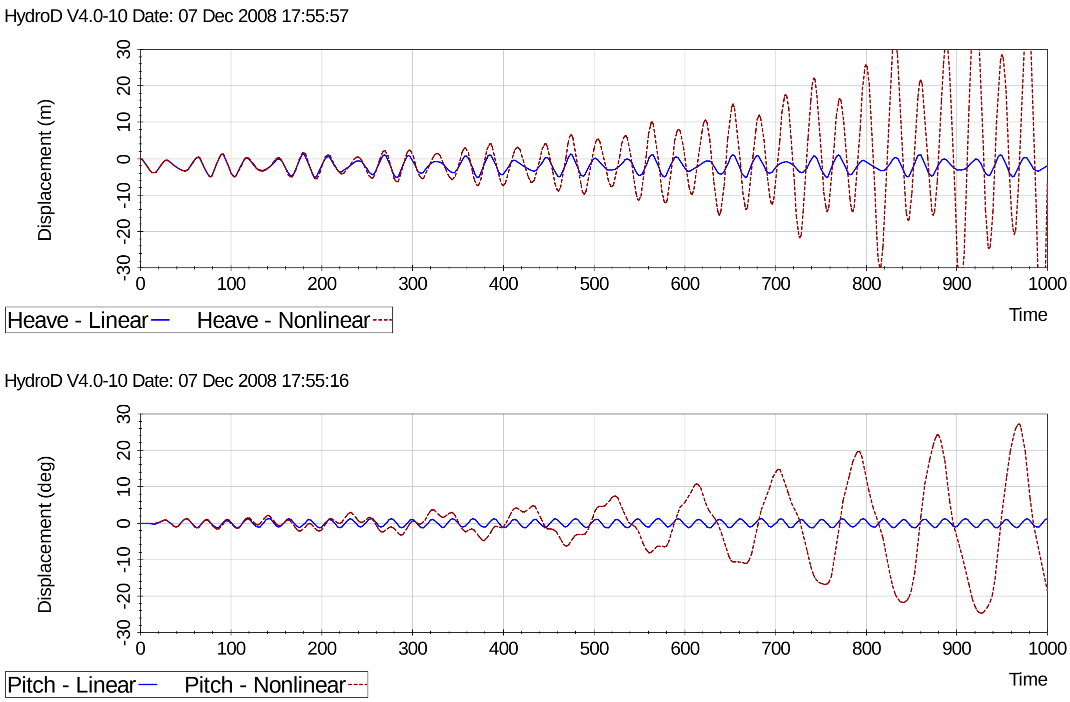

Figure 4: A comparison of the motion computed by Wasim nonlinear and linear option for a Spar buoy.

2 Load transfer in frequency domain for FLS analysis

When a full stochastic fatigue analysis is to be carried out, the loads needed for the structural analysis are the frequency domain loads. These are obtained from the time domain Wasim output by a harmonic analysis with linear solution.

An essential part of a stochastic fatigue analysis is to have a high quality load transfer. A good method for checking this is to compute the sectional loads by integrating the stresses computed by the Finite Element solver with the corresponding sectional loads computed directly. The integration of the stresses over the cut is done by the program Cutres. In Wasim these loads are computed by integration of the external loads and the inertia and gravity loads.

Full stochastic fatigue analysis can be carried out for specific details of the hull structure represented by local fine mesh model. The locations to be considered are decided based on the experience, review of drawings and/or fatigue screening of the global model.

The calculations are based on the direct load transfer from the wave load analysis to finite element models of the vessel and employ both global models to determine nominal stresses and deflections and local stress concentration models to determine hot spot stresses. All load effects are taken care of, and hence the method can be used for any type of structure. Full stochastic fatigue calculations are typically used for members with a relatively complex stress response such as hatch corners, discontinuous panel knuckles, tank covers and stiffeners subjected to large relative deformations. The method is also valuable for identifying fatigue prone areas through fatigue screening of the models.

The loads from the hydrodynamic analysis are transferred to the structural model as described earlier. Typically 12 headings and 20-25 wave periods for each heading are considered, resulting in 240 to 300 complex load cases.

The finite element analysis is run for all load cases to determine the stress transfer functions at each element of the model, $H_\sigma(\omega,\theta)$, which expresses the stress response per meter wave amplitude as a function of the wave frequency (ω) and heading (θ).

2.1 Global Analysis

The global model is a relatively coarse FE model of the entire vessel used to calculated nominal stresses and deflections in the main structure. Plating is normally represented by shell elements and stiffeners by beam elements. Typical element sizes are shown in Figure 5.

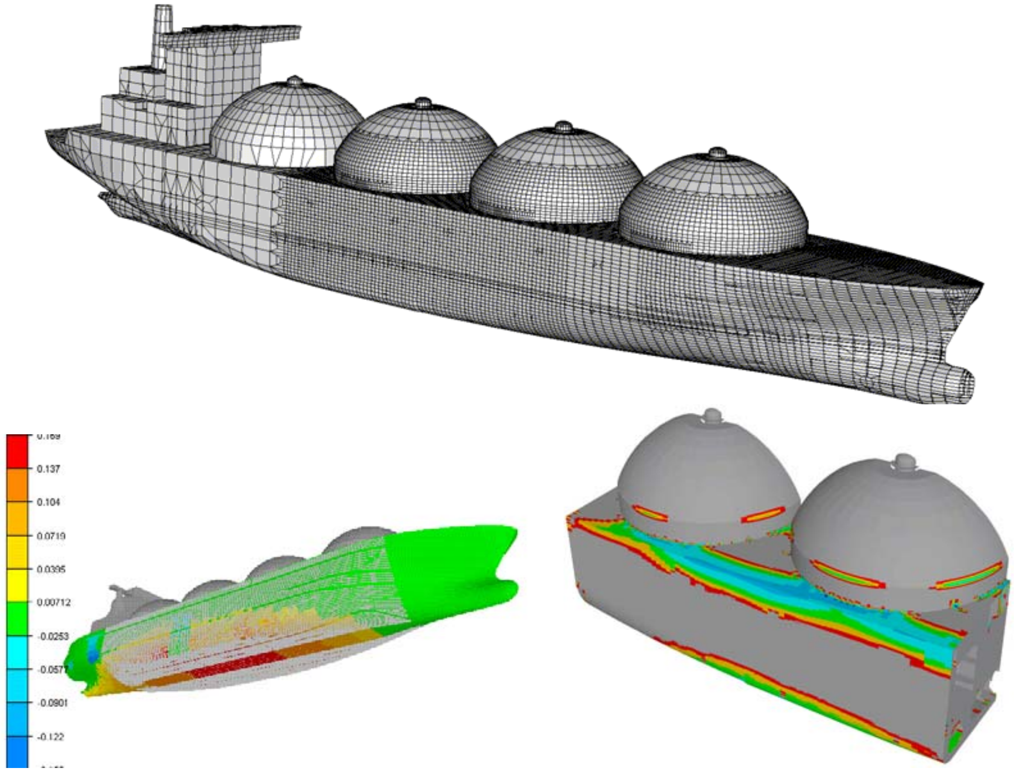

Figure 5: Typical mesh for a global model (top figure), an instance of hydrodynamic load transferred on global model by Wasim (down left) and fatigue prone areas in colour from the fatigue screening by Stofat (down right).

The lightship weight is normally represented by material densities applied to the shell and beam elements. Heavy components such as machinery may be represented by point masses. The model is divided into a sufficient number of sections and the mass of each section is adjusted according to the actual weight distribution. By iteration the convergence of the displacement, longitudinal and vertical centre of gravity, shear force and bending moment distribution is checked for compliance with the loading manual. The deadweight is represented by internal tank pressures automatically transferred by Wasim.

A prerequisite for correct load transfer from the hydrodynamic program is that there is sufficient compatibility between the hydrodynamic model (panel mesh) and the global structural model with regard to mass and buoyancy distribution.

Similar mass properties are ensured using the structural model as mass model in the hydrodynamic analysis. The final load equilibrium is checked by comparison of section loads as described earlier.

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2.2 Local Analysis

Local models are used as sub models to the global analysis and the displacements from the global analysis are automatically transferred to the local model as boundary displacements by using program Submod. In addition the local internal and external pressure loads and inertia loads are transferred from the wave load analysis.

From the local stress concentration models local geometric stress transfer functions at hot spots are determined. Element sizes in the order of the plate thickness are used for the details investigated to properly pick up the geometric stress increase.

The stress transfer functions, wave climate and S-N data are used to calculate the fatigue damage as a sum of part damages for each cell in the scatter diagram. Additional stress concentration effects which are not included in the finite element model, e.g. welding and misalignment may be included. The fatigue calculations are performed using Stofat, an interactive postprocessor performing stochastic fatigue calculation of welded shell and plate structures.

3 Ultimate Limit State (ULS) analysis

An ULS analysis investigates the ability of the structure to resist the action of the maximum expected loads or load effects during the design life of the ship. The limit state corresponds to the maximum load-carrying capacity (or strain, or deformation) under intact conditions. In case of a ship structural ULS analysis the strength analysis is to be carried out for the most extreme loading situation checking local structural areas as well as the complete hull girder capacity.

3.1 Environmental and operational conditions

Typically the North Atlantic Ocean is used as basis for the design environmental conditions and a lifetime of 20 or 25 years is mostly used. Of key importance in an ULS study is the identification of the most extreme loading situation. Here the loading condition of the ship, the speed and the wave headings are of importance. Using a linear response transfer function the expected lifetime extreme values can quickly be determined by straight-forward spectral and statistical procedures. From such an analysis it is usually easy to identify the worst heading and loading conditions for the various global responses. For local structural responses some care has to be taken as global responses will not always identify the worst conditions for local structural responses. Sometimes various loading or heading conditions need to be checked down to a FE structural analysis to evaluate local structural responses. The sustained speed of a vessel in a seaway depends on various factors, where both voluntary and involuntary speed reductions are of importance. Typically manoeuvring speed or even 0 knots is used when analysing the vessel behaviour in a 20 years storm. However it is recommended to assess different speeds in the linear hydrodynamic analyses, hence the effect of the speed is evaluated. This is of use when selecting a proper ship speed for the nonlinear hydrodynamic analyses. In the future it is expected that more advanced methods will be used, which estimate the voluntary and involuntary speed reduction in order to determine realistic operational conditions, see for example Pastoor et al [2].

3.2 Identification of critical sea states for nonlinear design assessments

Advanced nonlinear hydrodynamic programs are time consuming. Thus full scatter diagram assessments are simply not possible, not even with today's computer capabilities. Hence it is important that the amount of calculations can be reduced to one or a few short-term sea state analyses. This requires that the most critical sea states from a scatter diagram are identified. A series of nonlinear hydrodynamic simulations are conducted for sea states on the 20 or 25 years contour of significant wave height and wave period. By analysing the nonlinear response statistics the worst sea state can be selected.

3.3 Nonlinear design load simulations

Having identified the design sea state(s) for a nonlinear hydrodynamic analysis a design wave approach or random irregular simulations can be followed. The latter is rather straight forward. A time simulation is conducted of the nonlinear ship behaviour in a random irregular realisation of the sea state. Statistical post-processing of the response(s) is conducted from which expected extreme values can be determined. By simulating a long duration several incidents with high loads can be selected for load transfer to a FE model. Here the snapshot approach for the load transfer, as described earlier in the paper, is used.

For the design wave approach a conditioned regular or irregular approach are in use at DNV. The latter is preferred in most of the studies nowadays. A conditioned regular design wave is obtained by dividing the lifetime linear expected extreme response value by the transfer function peak value. This gives the wave amplitude. The wave period is taken as the transfer function peak. A regular nonlinear hydrodynamic calculation then gives a nonlinear correction factor and a snapshot load transfer can be applied. For responses with clearly peaked response transfer functions this method works well. For less pronounced peaked functions it can be unreliable. Furthermore this method is questionable regarding the inswing dynamics into the extreme event. The conditioned irregular design wave approach or better known as the MLER method (Most Likely Extreme Response) develops an irregular design wave by using the complete wave spectrum and transfer function. A more realistic inswing into the extreme event is then accounted for. The method conditions an irregular wave such that at a prescribed timestep the linear expected extreme occurs when a linear time simulation would be conducted. By simulating this wave with a nonlinear Wasim the corresponding nonlinear extreme is obtained at that time step. Of course many irregular waves can be developed, which induce the linear extreme at a pre-scribed time instance but in this method the most likely wave is predicted by using conditional statistical methods. See Pastoor [3] for more details and validation material of the MLER method. At the time instance of the extreme event a snapshot load transfer can be conducted for subsequent structural analyses.

3.4 ULS strength analyses

The ultimate strength of the vessel is based on loads as calculated in a hydrodynamic analysis as described above. This means that phase information is used also in the structural analysis. The various parts of the vessel will therefore be subject to simultaneously acting multi-axial sets of loads which calls for acceptance criteria capable of handling multi-axial load situations. The acceptance level for allowable tension stresses are therefore referred to a von Mises equivalent stress equal to 0.85-0.95 of the yield stress.

Buckling is checked by use of PULS [4] (Panel Ultimate Limit State). This is a semi-analytical computerized buckling code for assessing buckling and ultimate strength limits of stiffened panels subjected to the simultaneous action of in-plane loads in combination with lateral pressure. It is founded on advanced mathematical models and is implemented into easy and intuitive user interfaces.

The ultimate capacity and buckling strength limits are quickly assessed and supported by 3D graphics for improved understanding of the non-linear buckling phenomena. The code is recognized by several major Ship Classification Societies.

4 Conclusion

The time-domain nonlinear 3D hydrodynamic solver Wasim is introduced in this paper. The parametric rolling of a containership and Mathieu-type instability of a Spar buoy is captured by Wasim nonlinear calculation. The recommended practice of DNV for FLS and ULS analysis is presented. Linear load transfer in frequency domain from Wasim is adopted for FLS analysis, whereas nonlinear analysis is taken used for the most likely extreme responses in ULS analysis.

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