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Wave load predictions for marine structures

Timo Kukkanen

Abstract. In this paper hydrodynamic responses in waves for marine structures are briefly discussed. The aspects involved in the hydrodynamic wave loads and the predictions of the loads in the ultimate and fatigue strength analyses are given. Methods used in wave load predictions for the marine structures are presented. The main emphasis is in the global loads and especially in nonlinear wave loads. The methods to determine impact loads are also shortly reviewed.

Key words: Ship, offshore, structures, hydrodynamic, wave loads.

Introduction

In this paper an overview is given of the aspects in hydrodynamic wave loads in structural strength analyses in marine structures. The paper is focused on hydrodynamic responses in waves. Common practice in ship design is to determine the wave loads by applying rules and standards. The design rules and requirements are important to obtain international quality standards and design basis for ships. For example, Unified Requirements and Common Structural Rules for Bulkers and Tankers have been developed within International Association of Classification Societies (IACS) to improve safety of bulkers and tankers and to rationalise rules and requirements between different classification societies. In addition, Goal Based Standards for ship structures are under development in International Maritime Organization (IMO). Ship owners can set additional requirements and the designer has to prove that the ship will fulfil the requirements already in early design phase.

However, general standards and rules can be sometimes difficult to apply for unconventional ships. For example, size of the ships is increasing and new structural designs have been introduced. For complex structures and designs, direct calculation procedures are necessary. The direct calculation of the wave loads in the structural analysis is nowadays a common practice in the offshore industry. However, the direct calculation procedures, especially the calculation of the wave loads, are seldom applied in the shipbuilding industry. One reason is the rather large uncertainties in the wave load predictions for ships as well as lack of experience. In addition, the theoretical basis of the calculation methods are not necessarily sufficient to get reliable predictions. For example, the forward speed of the ship is not properly taken into account in the methods or the methods are based on linear theory so that extreme load predictions of the nonlinear responses are not possible. Furthermore, uncertainties exist also in all assumptions involved in stochastic methods and prediction procedures including environmental and operational conditions. Sometimes these are difficult to determine accurately in advance and hence assumptions need to be made to estimate life time conditions that have influence on fatigue and ultimate strength. Fatigue strength predictions can vary significantly depending on applied approaches and how different conditions are taken into account.

Aspects in wave loads for strength analyses of marine structures

Elements in the load and strength analysis of marine structures are presented in Figure 1. One of the starting points for the structural design and analysis of the ships and marine structures is to define environmental and operational conditions. For ultimate strength analyses, extreme environmental conditions have to be defined in order to obtain the design loads for structural analyses. Typically the extreme condition is the most severe sea state in the ship's lifetime that induces the largest stresses in structural details. Because different wave conditions or different types of loads might induce large stresses, several different conditions have to be considered. In a fatigue analysis, the whole operational profile of a ship is needed to obtain all the stress cycles that the ship will encounter during her service life. This means that all of the different loading and operational conditions in the ship's lifetime have to be considered. In addition, because the random nature of the ocean waves, probabilistic methods have to be applied in the analyses. To obtain predictions in reasonable time, the calculations are usually carried out in the frequency domain by linear methods. In addition, combined actions of several excitations can be obtained by linear superposition of responses due to separate excitation components (Kukkanen and Mikkola, 2004). Responses are linear with respect to excitation, if a change in the magnitude of excitation induces the same magnitude change for responses. However, in high waves the linearity assumption of wave loads with respect to wave height is not usually valid. If the responses are strongly nonlinear the determination of loads are usually carried out in time domain.

Environmental conditions are typically defined by the waves, winds and currents. Depending on the operation of the ship or marine structures some other factors can be equally important or even more important, e.g. ice or water depth. In here, the main emphasis will be focused on waves. The waves and their occurrence probabilities are normally given in wave scatter diagrams for different sea areas, for example, Global Wave Statistics (GWS, 1986). For the extreme wave loads of the ships, the International Association of Classification Societies (IACS, 2001) gives recommendations to use the wave data of the North Atlantic sea area. In rules, this sea area is usually defined as the worst sea area and it is intended to use to design ships for unrestricted service. Typically the North-Atlantic data is use for ultimate strength analyses but fatigue strength is predicted applying more realistic sea areas. If the route or operating area of the ship or marine structure is known in design phase site specific scatter diagram can be utilised.

The main operational conditions for ships are the speed and heading with respect to waves. The operational profile can vary considerably between different ship types. Depending of the ship type other operational conditions should be also taken into account, for example, loading conditions and time spent in harbour. Furthermore, voluntary speed reduction or possible restrictions in speed or heading in high waves should be considered in order to define extreme waves where the ship can safely operate.

The return period is defined as an event that is being exceeded on the average once every n-year. Usually the return period is used to define so called n-year wave defined by the wave height and the wave period. Thus, the n-year wave is a wave that is being exceeded an average once every n-year. The return period is not necessarily the same as the service time of the ship or marine structures. For example, in offshore structures the 100-year wave is one of the typical design conditions.

In ship structural design, the wave load and response predictions are often defined at the probability level of 10^{-8}. This corresponds of an occurrence that is expected to encounter once in 20-25 years. In the IACS recommendations (IACS, 2001) a return period of at least 20 years, corresponding to about 10^{-8} probability of exceedance per cycle is recommended to use for design wave bending moments. It can be noticed that the IACS recommendations relate the return period of 20 years and probability level of 10^{-8}. Thus, for ships the return period corresponds to the service time of the ship. However, for the offshore structures the return period is used for environmental conditions that occur seldom and hence including higher safety margin against loads. This is justified because ships can avoid the heavy weather changing the route but offshore structures should be able to withstand all possible weather conditions that might occur in the sea area during the service time.

The uncertainties in wave load prediction can be taken into account using safety factors, for example using extreme values with additional risk parameter instead of using the conventional most probable extreme value. The exceedance probability of the most probable extreme value is high, 63%. Thus, the risk parameter is applied to increase the safety margin in wave load predictions. Typically the risk parameter can be, for example, 1%.

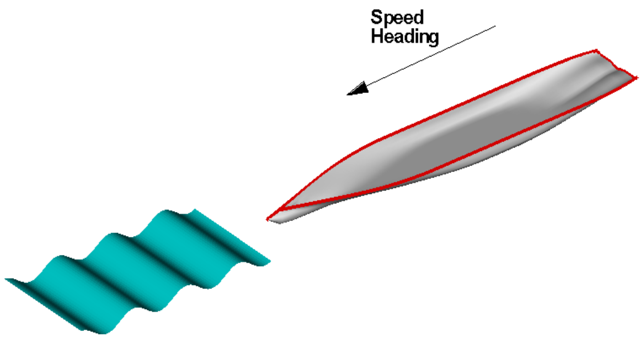
In addition, appropriate safety and usage factors are used in structural designs. In ultimate strength analyses, part of the structures can be designed above the elastic limits to allow some extent of plastic deformations. The safety margin can be higher for critical structures. It is important also to define the strength and fatigue criteria together with the safety factors in order to take into account all possible uncertainties in loads and structural designs.

The overall safety margin consists of the safety factors applied in the wave load predictions and in the structural designs. Because different safety factors can be used in different stages in structural design and analyses it is important to realise the overall margin of safety from environmental conditions to the strength criteria of structures. In addition, appropriate strength criteria and safety levels, i.e. safety margins or factor of safety, should be defined particularly if direct numerical methods are applied.

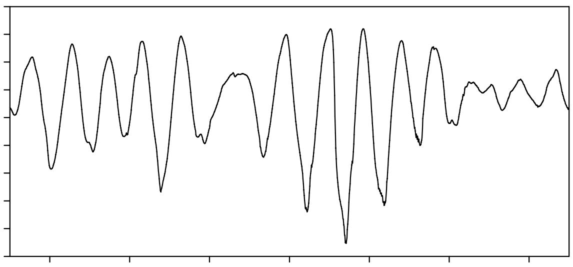
Environmental conditions

Wave height Hs (m)	Wave period, Tz (s) 4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
11.5							1		
10.5						1	1	1	
9.5					1	2	1	1	
8.5				1	2	3	3	2	1
7.5				1	4	6	5	3	1
6.5			1	3	9	11	8	4	1
5.5			1	9	19	20	13	6	2
4.5			4	21	37	34	18	7	2
3.5		1	13	45	64	47	21	6	2
2.5		4	31	77	80	44	15	4	1
1.5		11	53	78	51	18	4	1	
0.5	2	13	22	14	5	1			

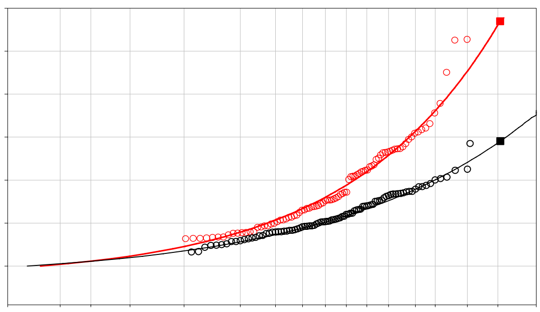
Operational conditions



Responses in waves



Extreme load and strength predictions



Fatigue strength predictions

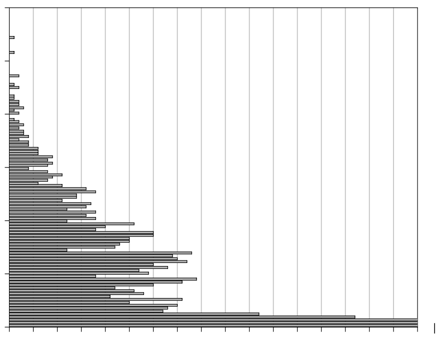


Figure 1. Aspects in load and strength analyses of marine structures.

Wave induced hydrodynamic loads and structural responses

The wave induced loads can be divided into hydrodynamic loads and induced responses depending on the dynamic behaviour and flexibility of the structure. For example:

Low frequency range: Period order of 100 s (~20 s →)
Wave frequency range: Period order of 10 s (~3 s ... ~15 s)
High frequency range: Period order of 1 s and below (~0.5 Hz ....~5 Hz →)

Examples of the time histories are shown in Figures 2 and 3 and the response spectra in Figures 4 and 5.

The low frequency loads are second order wave exciting forces inducing slowly varying rigid body motions. Typical responses are large motions, i.e. drift, in horizontal plane of moored offshore structures.

Typical wave frequency responses are the rigid body motions and accelerations. Loads are due to hydrodynamic pressures around the hull of the marine structure that induce local and global loads. The global loads are the shear forces and bending moments when the hull girder can be assumed to behave as a rigid beam.

The high frequency loads are impact type hydrodynamic pressure loads where the structural dynamic is important. The high frequency loads are, for example, springing and whipping loads, which induce dynamic and vibrating responses on the hull structures. In these cases, the elastic deformations of the structure have to be taken into account. Whipping is defined as a hull girder vibration in lowest natural frequencies due to wave impact. Springing is continuous vibration of the hull girder due to encountered wave excitation.

Ship structure’s stresses can be divided into global hull girder stresses and local structural detail stresses. The global and local stresses are usually called as primary and secondary stresses or in more detail as primary, secondary and tertiary stresses. For example, the primary stresses are affecting on the hull girder and secondary stresses on the whole double bottom. Tertiary stresses are affecting on the double bottom longitudinal stiffeners or on the bottom plate. Depending on what part of a structure is considered the wave loads have to correspond to the structural model in a consideration. For example, when hull girder loads are considered, the global wave loads are sufficient, but when local structural details are considered, the hydrodynamic pressure is also needed. Hull girder primary stresses are important part of the overall stresses in the structures and the allowable primary stress level defines the sensitiveness of a structure also against fatigue.

For ship type structures, an important wave induced response is the vertical wave bending moment that induces global hull girder stresses. If the hull girder has compression on deck it is called sagging condition and hogging if compression on bottom. The sagging bending moment occur if wave crests are at the bow and stern and hogging if wave crest is amidships. Typical example of time history in model tests for vertical bending moment amidships is shown in Figure 5 together with the calculation result based on the three-dimensional linear theory. In high waves, the linearity assumption of wave loads with respect to wave height is not usually valid. For example, the sagging moment is clearly larger than the hogging moment for high-speed ships in a heavy sea. The linear theories can not predict the differences between sagging and hogging moments. In the model test results higher order harmonic components are clearly visible and the time histories are not sinusoidal. The first harmonic component only without the mean shift can be obtained from the linear frequency domain wave load calculation methods. The linear methods can not take into account the body geometry above the mean water level especially the hull form changes at the bow and stern. In the linear methods, the ship geometry is defined up to the still water level. In addition, the forward speed of the ship change the steady pressure and wave profile around the hull. However, the most frequent waves are relatively low and the linear theory is sufficient in these conditions. These frequent load cycles are important for fatigue of ship structures.

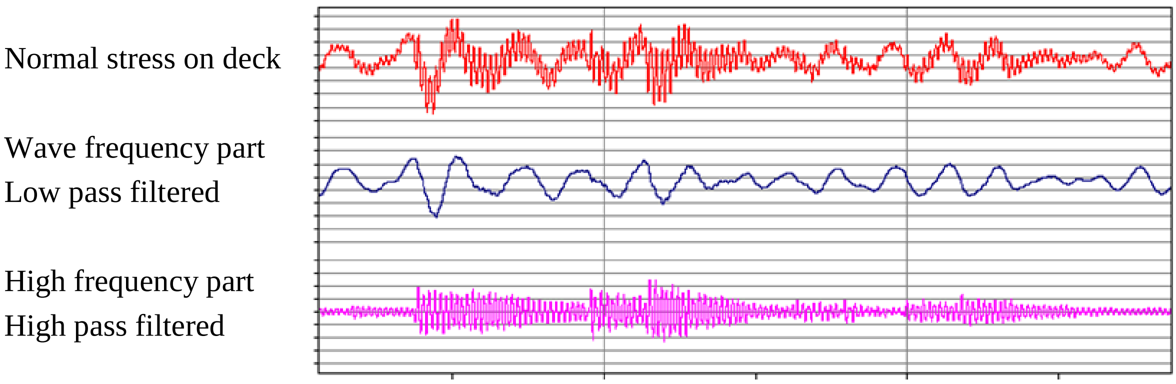


Figure 2. An example of high frequency response (whipping) measured in full scale.

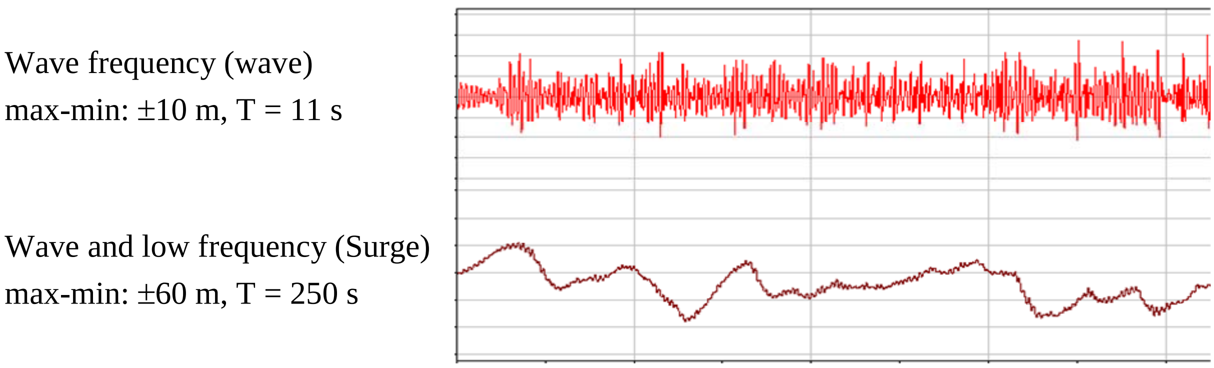


Figure 3. An example of low frequency response (surge drift) measured in model tests. Wave is given in the upper figure and the longitudinal motion (surge) in the lower figure

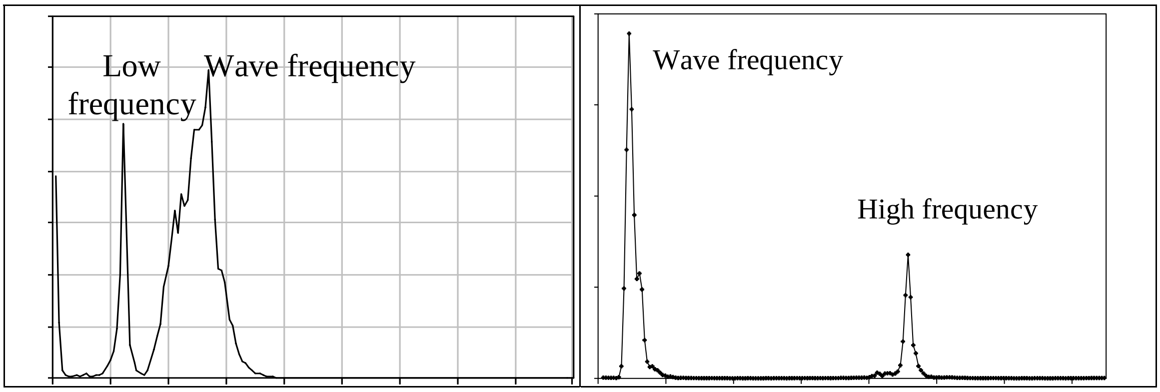


Figure 4. Typical response spectra for wave frequency responses including low frequency (left) and high frequency (right) responses.

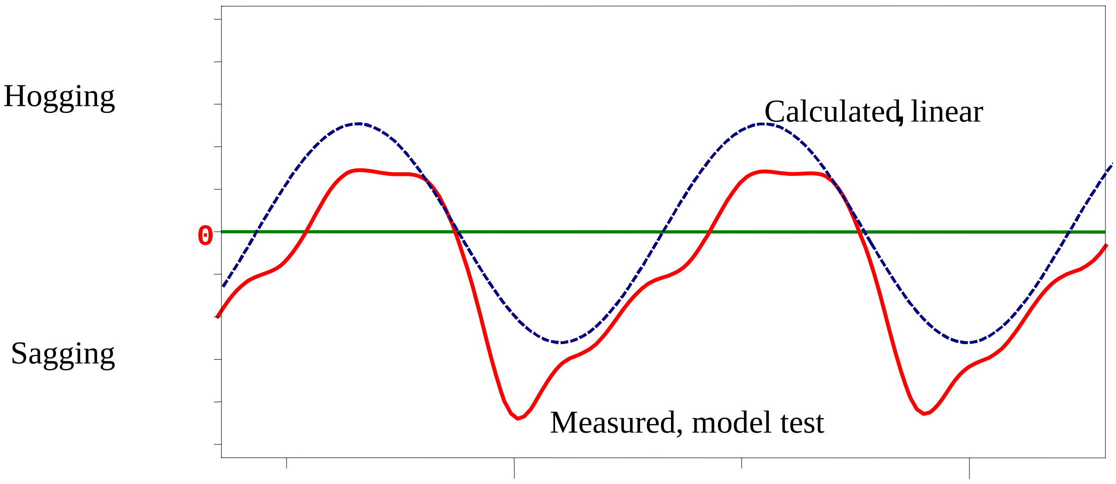


Figure 5. Typical example of time histories in regular wave model tests for vertical bending moment amidships and the linear calculation result.

Loads in wave frequency range

Background

Direct calculations of wave loads in structural analyses are generally based on linear theories but recently several different approaches have been developed to take into account nonlinearities in wave load predictions. Summary of different methods in seakeeping computations are given in Beck and Reed (2000) and state-of-art in wave loads in ISSC (2009).

A brief description is given here for the theoretical background of the boundary value problem of the moving body in water waves to give insight of the simplifications and their possible effects on the wave load predictions. Detailed derivation of the boundary value problem can be found, for example, from Newman (1978).

In practical applications, the methods applied in the wave load calculations are based on potential theory. Hence, it is assumed that the fluid is irrotational, incompressible and inviscid and hence the potential theory can be used to solve the flow around the body. The velocity potential has to fulfil the Laplace equation in the whole fluid domain and the boundary conditions at the free surface, bottom of the sea and infinity far away from the body. In addition, the velocity potential has to fulfil body boundary condition on the hull surface. Because the free surface condition has to be solved at the instantaneous free surface elevation around the body and the body condition has to be solved on the instantaneous wetted surface, the boundary value problem is nonlinear.

The kinematic free surface boundary condition is

$$\frac{\partial \zeta}{\partial t} + \frac{\partial \phi}{\partial x}\frac{\partial \zeta}{\partial x} + \frac{\partial \phi}{\partial y}\frac{\partial \zeta}{\partial y} - \frac{\partial \phi}{\partial z} = 0 \qquad \text{on } z = \zeta(x, y, t), \tag{1}$$

and the dynamic free surface boundary condition is

$$g\zeta + \frac{\partial \phi}{\partial t} + \frac{1}{2}\left[\left(\frac{\partial \phi}{\partial x}\right)^2 + \left(\frac{\partial \phi}{\partial y}\right)^2 + \left(\frac{\partial \phi}{\partial z}\right)^2\right] = 0 \qquad \text{on } z = \zeta(x, y, t), \tag{2}$$

where ζ is the free surface elevation, ϕ is the velocity potential and time is t. The vertical co-ordinate z is positive upwards. The free surface boundary conditions given by Equations (1) and (2) are non-linear. The linearized free surface boundary condition can be expressed as follows:

$$\frac{\partial^2 \phi}{\partial t^2} + g\frac{\partial \phi}{\partial z} = 0 \qquad \text{on } z = 0. \tag{3}$$

where the kinematic and dynamic free surface boundary conditions have been combined.

Linearization of the free surface and the body boundary conditions with respect to the wave amplitude means that the wave amplitude is assumed to be small compared to other length dimensions of the fluid and the body. In linear frequency domain methods, the body and free surface boundary conditions are linearized. When a linear theory is used, all hydrodynamic quantities are calculated up to undisturbed mean water level. Typically the solution of the linear problem is carried out in frequency domain and the boundary value problem is solved by using frequency domain Green functions. The Green function methods are based on Neuman-Kelvin theory (Beck and Reed, 2000). The Green function fulfils the other boundary conditions except the boundary condition on the body. Applying the boundary condition on the body the unknown source strengths can be solved. In the Green function methods, only the body surface is modelled by panels. The calculation is still time consuming when several different speeds, headings and frequencies are used.

The methods based on the potential theory are applied for the low, wave and high frequency range responses and loads. In cases where the viscous effects are important, such as in slender offshore structures, the viscous effects are usually taken into account applying Morison type approaches with appropriate drag coefficients.

The low frequency loads, e.g. second order excitation forces and moments, can be often obtained from the linear seakeeping codes in frequency domain. However, the responses in irregular waves need to be solved in time domain in order to determine the motions of the marine structures and then the induced responses in the structures.

Instead of solving the boundary value problem in frequency domain, time domain approaches can be applied also. Time domain representation of the Green function allows that the nonlinear body boundary condition can be applied. This means that the perturbation potential can be solved in the actual floating position and not only at the mean water line of the ship. In time domain, three-dimensional linear and nonlinear methods are presented by Ferrant (1991), Lin and Yue (1991) and Sen (2002).

In this paper, calculation results applying the nonlinear wave load method are given that was developed in the LAINE – project (Kukkanen, 2009). The method is based on the Neuman-Kelvin theory and time domain representation of the Green function. Additional nonlinearities due to the incoming wave elevation in Froude-Krylov and hydrostatic restoring forces and moments can be taken into account. The theory is based on potential theory and hence the motion of the fluid can be expressed by a single scalar function, i.e. velocity potential. Boundary conditions are applied at the boundaries of the fluid. The nonlinear free surface boundary condition is linearized but exact body boundary condition is applied on the body surface. Two co-ordinate systems are used; space fixed co-ordinate system, x,y,z and body fixed co-ordinate system x_0,y_0,z_0. The co-ordinate systems are shown in Figure 6. The hydrodynamic boundary value problem is solved in the space fixed co-ordinate system. Ship speed is U in the direction of x-coordinate and head seas is heading angle χ = 180 degrees. The six degrees of freedom body motions are surge (η_1), sway (η_2), heave (η_3), roll (η_4), pitch (η_5) and yaw (η_6) defined with respect to the space fixed co-ordinate system. The accelerations of the body can be solved from the equation of motion. The equation of motion is expressed in body fixed co-ordinate system and co-ordinate transformations are applied between body fixed and space fixed co-ordinate systems.

The boundary value problem is solved by applying Green's theorem and using panel method with unknown source strength distributions over the wetted body surface. The source strengths are solved using the body boundary condition. The most time consuming part is the solution of the time dependent Green function. Because of the time convolution integral the solution time is proportional to the number of panels N_P squared times the number of the previous time steps N_τ. At every time step $N_P^2 \times N_\tau$ evaluations of the Green function is necessary in the body nonlinear solution.

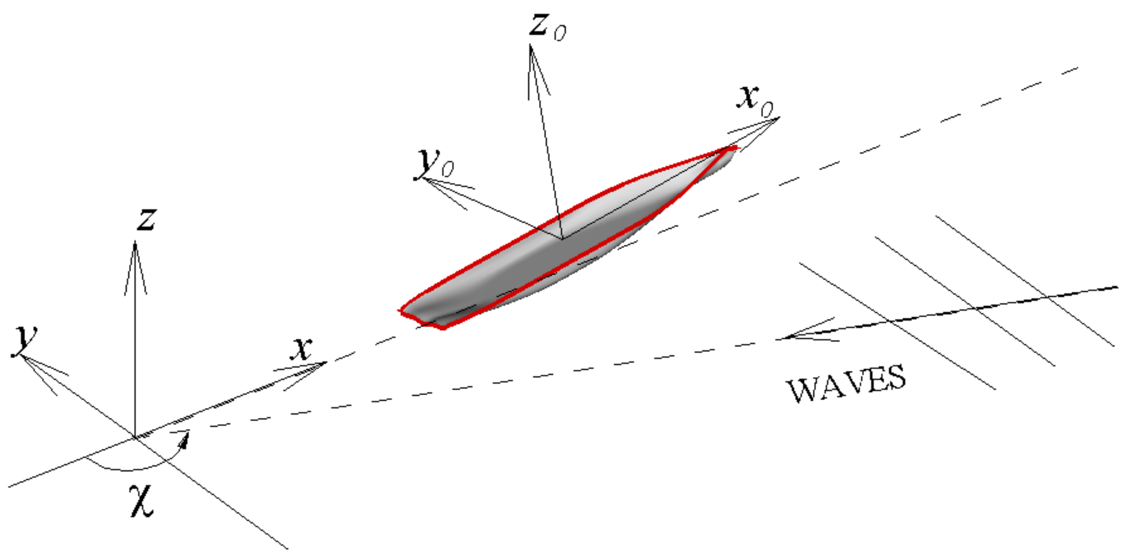


Figure 6. Co-ordinate system used in the time domain calculation method.

Application examples

The nonlinear wave load calculation method was applied to determine the wave loads for a ro-pax ship. Model tests were also carried out for the same ship model to measure ship motions and hull girder loads. The aim of the model tests was to investigate the seakeeping characteristics of the ship in waves and to obtain validation data for the nonlinear numerical calculations. Seakeeping model tests consisted of the experiments in irregular and regular waves and in calm water. Tests were carried out in head waves at zero and forward speed. The calculations were performed also in the same conditions and the calculated results were compared to the model test results.

Linear transfer functions were determined from the time domain calculations as well as from the model test results. Harmonic analyses were performed for both time histories obtained from the calculations and model tests. The first harmonic component gives the linear transfer function for the responses. Hence, the given transfer functions do not show directly any nonlinearities. In the harmonic analysis a Fourier series is fitted to the recorded data. The transfer functions or the response amplitude operators (RAO) are defined as the ratio of the response first harmonic to the wave first harmonic. The phase angle of the response is defined as the first harmonic component with respect to the wave amplitude at the centre of gravity of the ship.

Linear transfer functions at speed of Fn = 0.26 in head seas the linear transfer functions are shown for the vertical shear force and bending moment in Figure 7. The model tests were carried out at different wave amplitudes. The wave amplitudes are shown in the figures. The time domain calculations were carried out at wave amplitude of a = 3 m. The shear forces and bending moments are well predicted by the nonlinear time domain calculations at forward speed. However, the transfer functions include only the first harmonic component. Hence, the transfer functions do not give correct picture of the responses that can include also nonlinearities that can be presented only by the higher order harmonic components. Time histories of the vertical bending moment from the model tests and from the time domain simulations are shown in Figure 8 for two different wave amplitudes, a = 1 m and a = 3 m. The forward speed is Fn = 0.26 in head seas and the non-dimensional wave frequency is $\omega\sqrt{L/g}$ = 2.6 (λ/L = 0.9). In addition, the linear first harmonic component is also shown at the wave amplitude a = 3 m in the figure.

The nonlinearities in the responses were also investigated analysing separately the positive and negative amplitudes of the responses. The positive and negative amplitudes at the forward speed of Fn = 0.26 for vertical bending moment and shear force are shown in Figure 9. The calculated results are given together with the positive (Max) and negative (Min) amplitudes from the model tests. The calculation and model test results are given at wave amplitude of a = 3 m. Based on model test results in regular waves the sagging and hogging moment was well predicted by the nonlinear calculation method.

In addition of the model tests and calculations in regular waves, the validation was carried out also for the responses in irregular waves. The peak distributions of the response amplitudes from the model test and the calculations are presented in Figure 10 for the vertical bending moment amidships and for the vertical shear force at fore ship. The forward speed was 19.1 knots in the sea state of H_s = 5.0 m and T_z = 8.5 s. The forward speed results correlate well with the model test results.

The difference between sagging and hogging bending moments as well as in the vertical shear forces could be distinguished well. The sagging and hogging moment was well predicted at forward speed but it was noticed that the calculated results deviated from the model test results at zero speed. The difference can be due to the flat stern bottom close to water line. At the zero speed, the emergence of the flat stern out of the waves was clearly larger than if the ship has forward speed. The rapid change in geometry due to the relative motions is challenging in the calculations. Better results would be obtained if the number of panels was increased and smaller panel sizes were used.

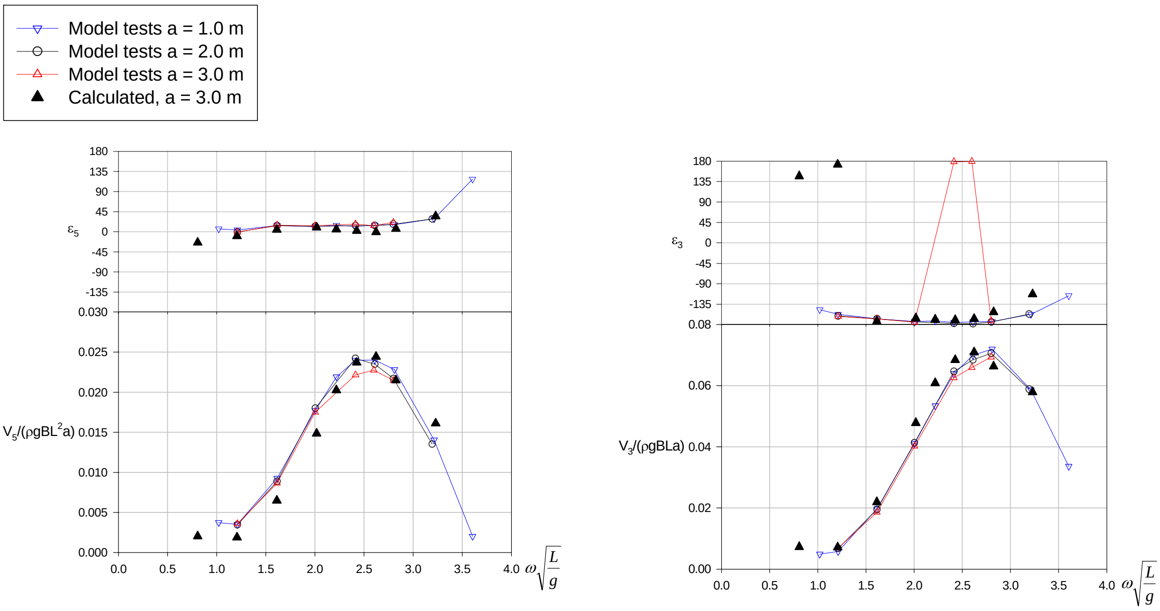


Figure 7. Non-dimensional transfer functions of vertical bending moment V_5 (left) and shear force V_3 (right) at Froude number of Fn = 0.26 in head seas. The phase angle with respect to wave is ε.

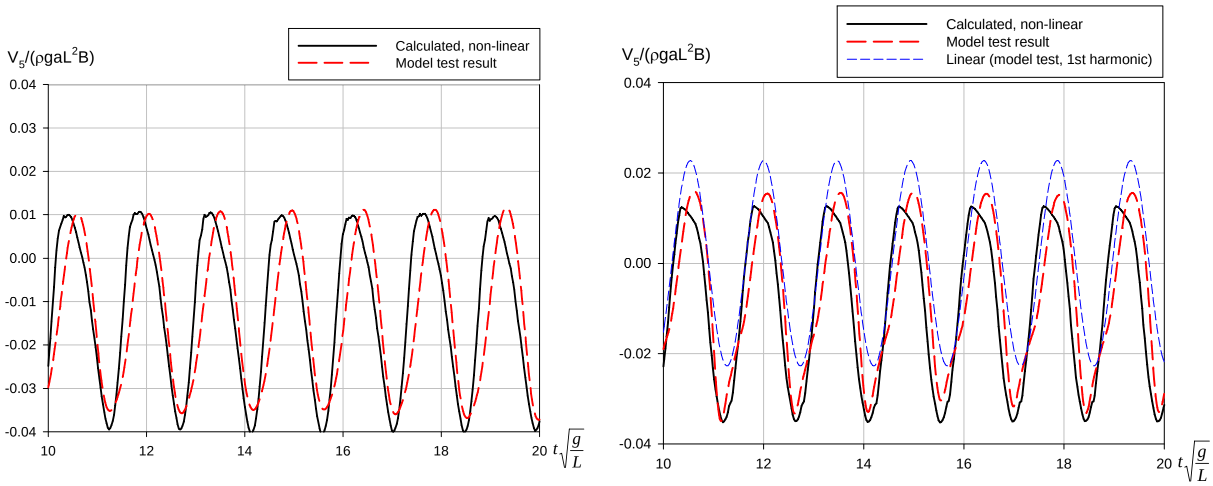


Figure 8. Non-dimensional vertical bending moment from model tests and calculations for the wave amplitude of a = 1 m (left) and a = 3 m (right). The non-dimensional wave frequency is $\omega\sqrt{L/g}$ = 2.6 (λ/L = 0.9) and the speed is Fn = 0.26 in head seas. The linear 1st harmonic component is shown also at the wave amplitude a = 3 m.

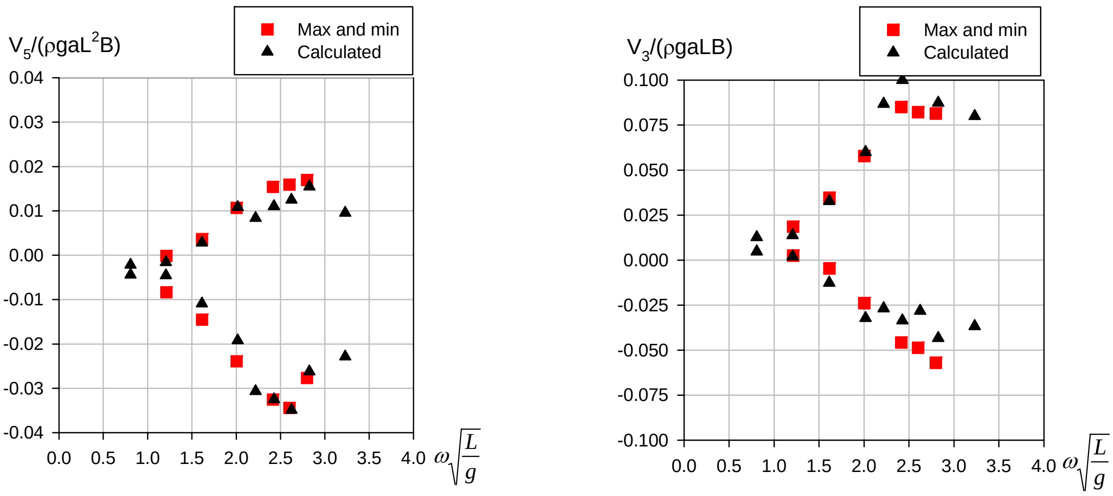


Figure 9. Positive and negative amplitudes of the non-dimensional vertical bending moment V_5 (left) and shear force V_3 (right) at speed of Fn = 0.26 in head seas. Wave amplitude was 3 m in model tests and calculations.

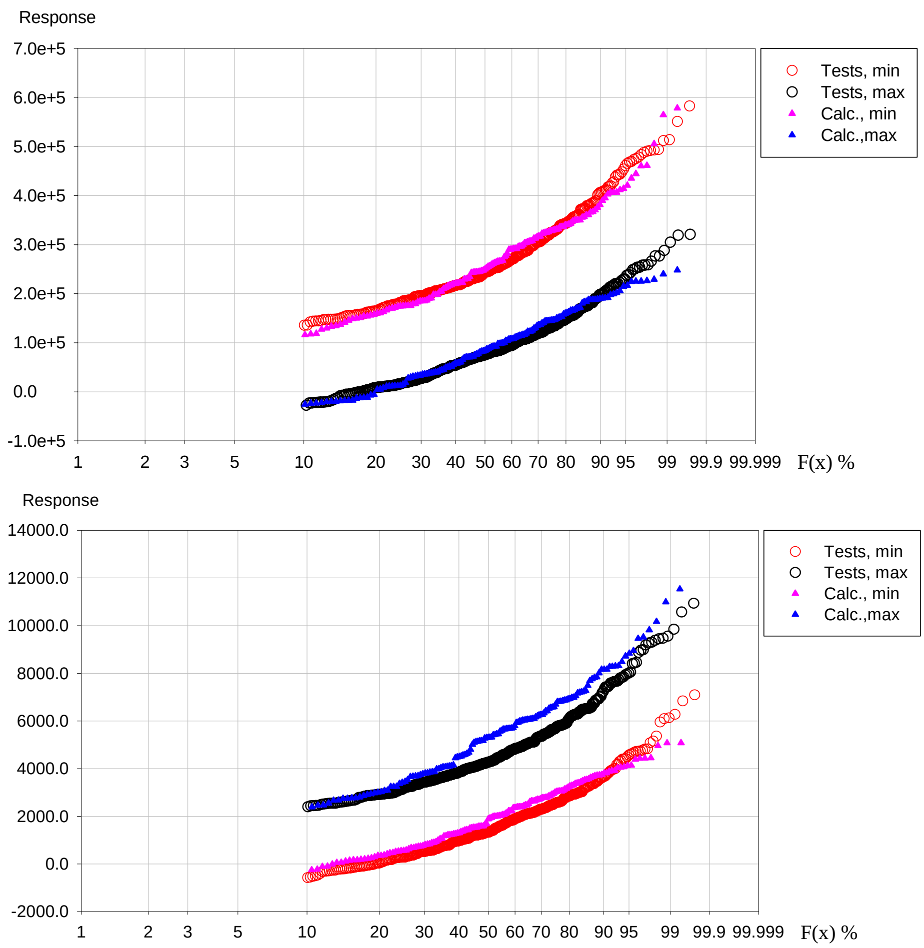


Figure 10. Amplitude peaks from model tests and calculations. Top: Vertical bending moment amidships (kNm). Bottom: Vertical shear force at fore ship (kN). Sea state H_s = 5.0 m and T_z = 8.5 s in head seas at forward speed of 19.1 knots.

Loads in high frequency range

The impact loads can occur, for example, at the bottom of the bow or stern of the ship or at the bow flare. The definition of the slamming is not necessarily straightforward and it is not always possible to distinguish the wave and high frequency wave loads. The methods to determine slamming induced loads are not yet well developed and the methods can not be applied easily in structural analyses. The slamming loads are important for local structures, such as stiffened plates, but also for global hull girder responses. The impact at bow or stern can induce whipping moment where the impact excites the first lowest eigenmodes of the hull girder. If the local or global structures are flexible, i.e. the duration of the slamming impact is shorter than natural period of the structure then the possible hydroelasticity have to be taken into account. Hydroelasticity means that the structural responses and deformations have influence on the hydrodynamic loads.

Challenging tasks to determine the impact loads are the short duration of impact pressure, time scale e.g. ~1 ms, and the small area where the impact pressure exist. Different methods applied in the slamming problems are given in ISSC (2009). Most of the methods are based on potential theory but also RANS codes (Reynolds averaged Navier-Stokes codes) have been applied. Comparison of different methods in slamming problems is given in Bizzolara *et al* (2008).

Here, shortly two-dimensional boundary element method is explained to predict impact pressure loads. The applied method is basically similar presented by Kim & Shin (2003) and Zhao *et al* (1996). The method is based on two-dimensional solution of velocity potentials when the body has constant downward velocity. Free surface elevation was updated using simplified equipotential boundary condition on the free surface. Velocity potential is solved by boundary element method and the free surface is updated by mixed Euler-Lagrangian method. Fourth-order Runge-Kutta method is used in the numerical solution to solve the boundary value problem at each time instant. Hydrodynamic pressure is calculated from Bernoulli's equation. The hydrostatic buoyancy pressure was ignored.

Slamming pressure was calculated for wedge with deadrise angle of 25 degrees. Straight line segments were used to model the body and the free surface. Half body and free surface included 51 and 100 nodal points, respectively. Non-dimensional impact pressure is shown in Figure 11 together with similarity solution presented in Zhao and Faltinsen (1993). The present simplified method gives somewhat higher predictions for the peak pressure than the similarity solution.

In slamming problems the correct free surface elevation during the water entry is important in order to obtain reliable predictions for the impact pressures. The presented method is based on the so called Wagner approach, i.e. the free surface elevation is taken into account. In the von Karman approach the impact pressures are solved without taking into account the free surface that is rise up due to the body entry into the water. The von Karman approach gives too low predictions on the impact pressures. The importance of the free surface elevation can be seen in Figure 11 where the highest pressure occurs well above the mean water level. The non-dimensionalised vertical co-ordinate of the mean water level is $y/Vt = 0$.

The free surface elevation at the bow impact include significant water spray deformation or jet flow due to high water flow velocities at the body and free surface intersection. However, inside of the jet flow the pressure is close to the atmospheric pressure and the influence on the responses is insignificant. The flat bottom impact the local pressures can be very high but it has not necessarily significant contribution on the global forces, i.e. the duration of impact is short and local so that the total impulse is moderate. At higher forward speeds the bow submergence and bow impact have obviously larger effects on global hull girder loads than zero-speed stern impacts.

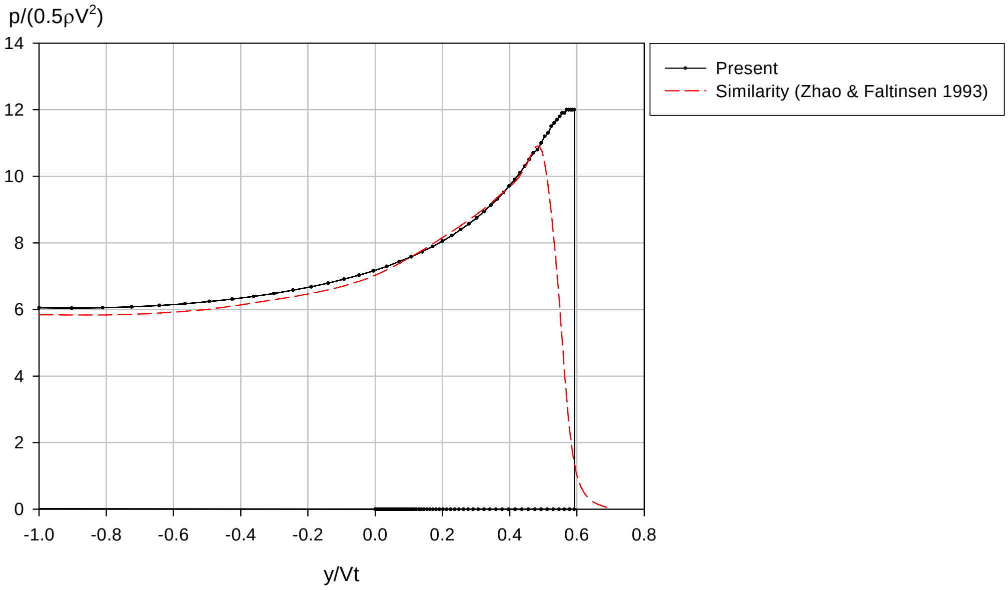


Figure 11. Non-dimensional slamming pressure for wedge of deadrise angle 25 degrees. The impact velocity is V. The vertical coordinate is y and the apex of the wedge is at the y = -1. Still water level is at y = 0. Time is t and water density is ρ.

Conclusions

This paper was focused on the hydrodynamic loads and responses in waves. The different load types and the calculation methods were shortly reviewed. Most of the methods in practical applications are based on linear frequency domain theory. Linear frequency domain methods are well known and the methods give good results for ships and offshore structures at zero speed. For offshore structures direct calculation methods are applied in practice in structural design. At forward speed and especially at high forward speeds, the methods are not yet applied commonly in practice.

New methods for nonlinear load effects and methods for impact loads have been developed but still further research is needed to understand the nonlinear phenomena and to develop methods in practical applications. The results obtained from the time domain nonlinear wave load calculation method correlate well with the model test results. The calculation method can predict the important responses that are needed in the structural analyses. The calculations and the analyses showed that the method can be applied in demanding structural analyses. Linear frequency domain methods are still important to define the design sea states for different responses in hydrodynamic analyses. Systematic calculations and further investigations should be carried out to investigate the effect of the different calculation parameters as well to investigate the theoretical approaches to model the physical phenomena correctly.

Acknowledgment

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Timo Kukkanen
VTT
PL 1000, Tietotie 1 A
02044 VTT
FINLAND
Timo.Kukkanen@vtt.fi