Non-linear hydro load correction for Spectral Fatigue Analysis

Marta Nowacka

August 2019

Master Thesis

presented in fulfillment of the requirements for the double degree:

“Master in Mechanical Engineering, specialized focus in Advanced Ship Design”
conferred by University of Liège,

”Master in Mechanics specialized in Hydrodynamics for Ocean Engineering”
conferred by Ecole Centrale de Nantes,

developed at Damen Schelde Naval Shipbuilding, Vlissingen,

in the framework of the “EMSHIP” European Master Course
in “Advanced Design in Ship and Offshore Structures”.

Executive Summary

released for a public access

Contents

Abstract

A non-linear correction to a long-term response of a vertical wave-induced bending moment of a vessel is investigated within this study. Various methods of calculating a bending moment with the non-linear effects accounted are described and based on the literature review, the most applicable method is selected. The details of the implementation of the chosen method are then presented. The first attempt to validate the created code is undertaken with the complete time domain analysis results. Furthermore, a detailed investigation of the methodology of performing the time domain simulations is performed in order to improve the quality of the solution. Based on the conclusions from this study, an improved linear and non-linear analysis is performed and the results from both approaches are compared and assessed. Finally, the efficiency and applicability of the implemented approximate method are investigated, especially for fatigue calculations purposes.

1 Introduction

The objective of this work is to find and implement a method to calculate a long-term response of the wave-induced bending moment with the non-linear effects accounted within the computational time reasonable for the industrial applications. A general background of the topic as well as the motivation to undertake this study are described in order to outline the starting point of the presented dissertation.

As shipbuilding is an industry with a very long history and tradition, a design process throughout the years was based on the experience and modifications of the existing designs by extrapolation to the newly constructed vessels. Nowadays, Classification Societies have undertaken the role of setting up the rules that should be followed to create a new safe design. Evidently, the regulations regarding the assessment of the wave-induced hydrodynamic loads acting on the ship hull are also specified by the Classification Societies. The estimation of hydrodynamic loads is usually provided in the form of empirical formulas derived based on a great variety of existing ship designs and as such, this method is of course highly simplified, [1]. Even though that approach is sufficient for numerous conventional designs, it is not very accurate for more advanced vessels and can lead to improper estimation of acting loads. The solution to that problem offered by Classification Societies, is to apply very high safety factor which would obviously result in not optimised design. An alternative to this approach is to perform a direct hydrodynamic loads calculation which allows to create a safe and optimised design. However, a direct analysis requires of course much longer computational time, very often too long to be acceptable for the industrial applications. Nowadays, since the computational power is increasing and the direct analysis becomes more feasible, a growing interest is directed towards it by many parties.

The most common method to evaluate the hydrodynamic loads with direct computations is to perform a frequency domain analysis within the potential flow theory assumptions. This method can provide the solution quite fast, but it is a fully linear approach. If the non-linear effects should be accounted it is necessary to perform calculations in a time domain, yet this type of analysis requires much longer computational time, making this approach impractical for industrial projects. Numerous research studies thus focus on developing the methods that can account for the non-linear effects in an efficient way, providing satisfactory results within reasonable computational time. An attempt to implement such an approximate approach is made within this thesis and the achieved outcome is presented in the following chapters.

2 Calculation of a long-term response of the wave-induced bending moment

In this work, the interest is focused on the long-term response of the bending moment, thus the theoretical foundations to calculate it based on the direct hydrodynamic calculations are explained in this section. A procedure to compute a long-term probability distribution consists of a few steps that slightly differ for the frequency and time domain analysis. In general, firstly the seakeeping computations have to be performed and then, short-term responses can be derived based on the output of the simulations. The long-term response can be then calculated from the obtained short-term responses. A detailed methodology to assess the long-term response is explained further.

Short-term response

The first step of the long-term response calculations of the hydrodynamic loads is to perform frequency or time domain analyses for the entire range of the conditions encountered by the ship. The frequency domain computations are conducted for all the combinations of ship speed and heading, while the time domain simulations need to be performed for every combination of speed, heading and sea state. From the output of the frequency and time domain analysis, the short-term probability distribution can be obtained but the procedure differs for both cases, thus it is described separately below.

Frequency domain analysis

In the frequency domain calculations, a model is subjected to a regular wave of a given frequency and the analysis is performed for a specified range of frequencies with a certain sampling interval. A separate computation has to be done for each combination of required ship speed and heading. The output of each analysis is a transfer function called Response Amplitude Operator. RAO is a ratio of the amplitude of the response of the body (translational or rotational motions, bending moment, etc.) to the amplitude of excitation usually represented graphically as a function of wave frequencies or periods. An irregular sea state can be described by the wave spectrum, which represents how the energy is distributed among frequencies in a given sea state. A few theoretical spectra exist describing specific sea conditions, for example, a Pierson-Moskowitz spectrum corresponds to fully-developed seas, while a JONSWAP spectrum is better adjusted to seas with a fetch limitation, [1]. The spectra are usually defined as a function of two parameters: significant wave height H_S and peak period T_P or frequency ω_P (spectra can be also expressed as a function of mean wave period T_1 or zero up-crossing period T_2). The short term response can be obtained by multiplying the square of the transfer function $H(\omega)$ with the wave spectrum $S(\omega)$:

$$S_X(\omega) = S(\omega) \cdot |H(\omega)|^2 \tag{2.1}$$

The short-term statistics can then be derived from the response spectrum using the Rayleigh distribution. The Rayleigh probability density function (*pdf*) of a variable x (for example bending moment M_y) is given by, [1]:

$$p(x) = \frac{2x}{\epsilon} \exp\left(\frac{-x^2}{\epsilon}\right), \tag{2.2}$$

with the Rayleigh parameter $\epsilon = 2\sigma^2$, where σ^2 is a variance of the response spectrum. The variance is related to the zeroth moment of the spectrum which is equal to the area under the curve of the spectrum:

$$\sigma^2 = m_0 = \int_0^\infty S_X(\omega)\mathrm{d}\omega \tag{2.3}$$

The probability that the variable x exceeds certain threshold x_0 can be assessed using the complementary of the cumulative distribution function:

$$Q_{ST}(x > x_0) = 1 - Q(x \le x_0) = \int_{x_0}^\infty p(x)\mathrm{d}x \tag{2.4}$$

In case of a Rayleigh distribution this is equal to:

$$Q_{ST}(x > x_0) = \exp\left(\frac{-x_0^2}{2m_0}\right). \tag{2.5}$$

Time domain analysis

In case of the time domain analysis, a model can be subjected to an irregular wave that is generated based on a wave spectrum and thus the calculations are performed for a specific sea state, characterised by significant wave height and peak period. An output of the analysis is a time signal of a response. The short-term statistic can be obtained by extracting the extremes from the signal and performing a fitting to the probability density function. The time signal as an output allows to divide the results for the hogging and sagging conditions which is not possible in the frequency domain analysis, [1]. As mentioned before, Rayleigh distribution can be applicable in case of the linear calculations. In case of the time domain analysis, a better choice is a Weibull distribution that describes better the non-linear processes, [2]. The Weibull probability density function is characterised by two parameters: shape parameter λ and scale parameter η:

$$p(x) = \frac{\lambda}{\eta}\left(\frac{x}{\eta}\right)^{\lambda-1} \exp\left(-\left(\frac{x}{\eta}\right)^{\lambda}\right), \tag{2.6}$$

The Rayleigh distribution is a special case of the Weibull distribution with $\lambda = 2$ and $\eta = \sqrt{\epsilon}$. Similarly, the exceedance probability can be obtained via cumulative distribution function:

$$Q_{ST}(x > x_0) = \int_{x_0}^\infty p(x)\mathrm{d}x = \exp\left(-\left(\frac{x_0}{\eta}\right)^{\lambda}\right). \tag{2.7}$$

Long-term response

The short-term probability distribution corresponds to the situation when the ship encounters only one sea state and keeps the same heading and speed all the time. Of course, different conditions and sea states are encountered and thus all of them have to be evaluated in order to assess the long-term statistics. A long-term response is thus computed as the combination of the short-term probabilities for all the different conditions. Here, the probability of occurrence of various ship and wave conditions should be taken into account. The probability of encountering the specific sea state $p(H_S, T_P)$ can be assessed using wave scatter diagrams representing the occurrence of a certain combination of specific wave height and period (throughout the work [1], a sea state was characterised by a zero up-crossing period T_2 and the same is kept within this work as the same wave scatter diagrams are used). Then, the probability of occurrence of a certain ship speed $p(V)$ can be assessed knowing the operational profile of the ship. The probability of occurrence of different headings $p(\mu)$ is very often assumed as equiprobable, but if a vessel has a very specific regular route, the more detailed probabilities can be also assessed. The formula to obtain the long-term probability of exceedance is thus the following, [1]:

$$Q_{LT}(x > x_0) = \int_{x_0}^{\infty} \int_{i} p_i(x|i) \cdot p(i) \mathrm{d}i \mathrm{d}x = \int_{i} Q_{STi}(x > x_0) p(i) \mathrm{d}i \tag{2.8}$$

where $p_i(x|i)$ is the short-term probability of variable x for condition i and $p(i)$ is the probability of occurrence of condition i:

$$p(i) = p(H_s, T_2) \cdot p(\mu) \cdot p(V). \tag{2.9}$$

3 Methods of evaluating the wave-induced vertical bending moment

The numerous methods of calculating the wave-induced bending moment exist, with different level of complexity and accuracy. In order to provide a better understanding what these method can account for and on which simplifications some of them are based, firstly, the brief description of the non-linear effects related to the ship motion is presented. Consecutively, the various approaches to bending moment assessment are described. Among those the empirical methods, the direct calculation of loads and the approximate methods are distinguished.

Empirical and semi-analytical methods

The simplest and fastest way to estimate the design wave-induced bending moment is provided in the form of empirical formulas by the Classification Societies such as Bureau Veritas (BV), Lloyd's Register (LR), Det Norske Veritas-Germanischer Lloyd (DNV-GL). The bending moment is assessed based on the various parameters of the ship hull such as length, breadth and block coefficient. Operation conditions can also be taken into account through various navigation and service restriction coefficients. The distinction between sagging and hogging condition can also be obtained. The drawback of this approach is that only one single value of the bending moment is obtained instead of the probability distribution.

The other very simplified approach is to use closed-form expressions defining the frequency response functions for the wave-induced bending moment [8]. The formulas are obtained in a semi-analytical way, based on the linear strip theory and can be evaluated using the spreadsheet program. As an input, they require some basic parameters of the ship thus they can be useful to estimate the bending moment at a conceptual design stage. The advantage over the formulas proposed by the rules is that this method is adapted to estimate long-term response and therefore it can take into account the operational profile of the vessel and the wave scatter diagram. The method though obviously gives just an estimate of the bending moment and if more accurate values are of interest, the direct calculations have to be performed.

Direct calculation methods

The direct analysis can provide much more accurate values of the wave-induced loads, however it is inextricably linked with much higher computational cost. The most precise values can be obviously obtained from a fully non-linear solution. The most advanced method is the approach assuming viscous fluid, as it has an advantage of taking into account implicitly strong non-linear effects as wave-breaking or slamming. Nevertheless, this approach still encounters numerical problems and the computational time is too large to consider this method in practical applications, [7, 9].

Consequently, the seakeeping problem is usually solved under the assumption of the potential flow, where strip theory, free surface Green function or Rankine panel methods can be used, [4]. Strip theory is the simplest method, based on a two-dimensional approach, applicable for slender ships. It has also difficulties to solve problems with forward speed. Panel methods are a 3D methods that can account for a speed of the vessel. The Green function method requires panels only on the surface of the hull but the derivation of the Green function is a difficult task. In Rankine panel method the panels have to be distributed over both the hull and the free surface. It is better adjusted to the problems with forward speed than the Green function methods, [4, 6].

Within potential flow formulation, different levels of taking into account non-linear effects are possible. Fully linear solution can be obtained by solving the problem in a frequency domain and this approach has a benefit of being much faster than the time domain analysis. If the non-linear effects are to be accounted, the time domain calculations have to be performed, however, a fully non-linear methods still require a huge computational effort and they are yet not available for practical cases, [4, 5, 9]. Therefore, there are also methods that linearise the free surface boundary condition, while the body condition is non-linear by being satisfied on the instantanous wetted surface area. In this approach the Froude-Krylov and restoring force are computed as non-linear since they are obtained by integration of the incident wave pressure over the instantaneously wetted surface, [4]. The radiation forces can be kept linear and they can be computed based on the frequency domain solution.

In time domain approach, the additional highly non-linear effects, as slamming and green water, can be also included in a simplified way. It can be achieved by the 2D methods based on approximate or analytical models, that accuracy depends on various parameters as the shape of a body or deadrise angle of impacting the water, [3, 10]. There are also possibilities to couple potential flow results with the CFD codes to compute the slamming loads but that is of course more advanced and time-consuming, [11].

Approximate methods to assess a non-linear bending moment

As a complete time domain analysis including the non-linearities of the system is still a very time and CPU consuming process, there are numerous attempts to develop a method allowing to assess the long-term wave-induced bending moment correctly within shorter time. The different methods found in the literature are described here, along with their advantages and drawbacks to enable a conscious selection of the most applicable approach.

4 Selection of the method and implementation

After the literature review of the existing methods of the bending moment calculations, the conscious selection of the most applicable approach could be made. The software available in the company was also considered here, in order to create a tool consistent with the already used approach. The level of accuracy versus the computational time of the method should of course be accounted. These considerations are presented in the first parts of this section. Later on, the implementation of the method and the created code are described.

5 Validation with the reference results

In this section an attempt is made to validate the created code with the reference results of the complete time domain analysis. In order to compare the results of both analyses, the model, settings and methodology were the same as in the reference, based on the available database and information included in [1].

In the first part of this section the description of the model and parameters of the seakeeping simulations are consistently summarised. Then, the postprocessing part of the code is verified based on the database from the reference analysis. Finally, the complete code is tested and the seakeeping computations are launched afresh. The discussion of obtained results is presented and the conclusions allowing to proceed to further studies are drawn.

The considerations presented in this section allow to state that the created code is able to correctly compute the long-term probability distribution based on the database of the time signals. It was shown that the approximate method is correctly implemented and that in the case of the reference analysis, the accurate results can be achieved much faster compared to complete time domain computations. That confirms that the selected approximation method can give a significant gain in the computational time needed to obtain a long-term distribution of the bending moment with the non-linear effects accounted.

However, a closer investigation of the results indicates that some of the time signals might be unphysical and lead to incorrect values of bending moment long-term distribution. That indicates that something might be missing in the followed methodology or settings of the model. Therefore, the next section is dedicated to a closer investigation of the overall procedure of the performed analysis.

6 Investigation of the correctness of the performed analysis

As with the current simulation model and methodology, the obtained results differ from the expected ones, the review of some important settings and overall approach was performed. Several issues are raised and discussed in this section in order to verify certain details of the conducted analysis. The following issues were raised:

- Discretisation of the model and computational domain,
- Modelling of buoyancy, weight and moment of inertia of the vessel,
- Selecting correct values from the output files,
- Roll damping,
- Impose motion options,
- Methodology of fitting the data to a probability density function,
- Version of the software.

The investigations revealed several issues that should be accounted in the performed frequency and time domain analysis. The discovered solutions were implemented within the followed approach in order to improve the quality of the performed calculations. The user has a possibility to choose between different options and guidelines are also provided which approach should give the best results.

7 Improved analysis

Based on the findings of the previous section, the new analysis is set accounting for all the improvements. The results of the frequency and time domain analysis are presented, as well as the investigations of the efficiency of the approximate method.

The improvements introduced based on the investigation performed in section 6 allowed to obtain the results that can be qualitatively assessed as correct.

Additionally, the results were evaluated with different postprocessing options implemented within the code which was concluded with the recommendations for the users.

Finally, the investigation of the efficiency of the approximate method was conducted. It was found that the convergence can be achieved much faster for smaller probabilities of exceedance than for higher. However, in any case, the results can be achieved significantly faster than comparing to the complete non-linear analysis. The methods to assess the level of accuracy achieved with the approximate approach were also proposed.

8 Conclusions

The purpose of the presented study was to implement a method to calculate a non-linear correction of a long-term response of bending moment within the time feasible for the industrial applications. The review of the various existing methods allowed to select the approach that was expected to be the most efficient for the required purposes.

The code allowing for a fully automated approximate analysis with the approximate method was implemented in consistency with the tools used in the company. The non-linear correction can be thus easily implemented within the already existing workflow of calculating the fatigue damage. It was attempted to create a tool that would be universal and as general as possible to facilitate its usage for further applications. The different ways of conducting the analysis and post-processing of the results are also provided with an easy way of selection of the desired option.

A thorough investigations of the model, seakeeping analyses settings and postprocessing methodology was conducted. Numerous parameters were investigated and the adequate findings were implemented within the created tool.

A new analysis was performed for both frequency and time domain with all the conclusions from the investigation of the approach accounted for. Thanks to these improvements, the obtained results are qualitatively correct.

The performed time domain analysis could serve as a validation for the implemented approximate method. A thorough study of the convergence and the tools to assess it was presented. It was shown that the approximate method can provide the estimation of the non-linear bending moment very fast for small probabilities of exceedance. However, for smaller probabilities the analysis is significantly extended. The savings in time compared to the complete non-linear analysis are though evident and it can be concluded that the created tool is able to efficiently estimate the non-linear long-term bending moment response for the fatigue calculations purposes.

It can be concluded that the main objective of the work was achieved − a tool to estimate a non-linear bending moment within the time acceptable for the industrial applications was created. The code is efficient, universal and consistent with the approach existing in the company, therefore it can be directly incorporated within the work flow of calculating the fatigue damage for the commercial projects.

References

1. Internal DSNS document.

2. Sagli, G., *Model uncertainty and simplified estimates of long term extremes of hull girder loads in ships*, PhD Thesis. Norwegian University of Science and Technology, Trondheim, 2000.

3. Tuitmam, J. T., *Hydro-elastic response of ship structures to slamming induced whipping.* PhD Thesis, Delft University of Technology, 2010.

4. Pastoor, L. W., *On the assessment of non-linear ship motions and loads*, PhD Thesis. Delft University of Technology, 2002.

5. Kim, Y. et al, *Time-domain analysis of non-linear motion responses and structural loads on ships and offshore structures: development of WISH programs.* International Journal of Naval Architecture and Ocean Engineering, 2011, 3:37-52.

6. Simonis, H., Marleaux, P. Abdel-Maksoud, M., Lecture slides to the course *Seakeeping of ships*, Technische Univeritat Hamburg-Harburg.

7. *Whipping – Simulation*, Safety4Sea, 2016. Online: https://safety4sea.com/whipping-simulation/, access: 27.03.2019.

8. Jensen, J.J., Mansour, A.E., Olsen, A.S., *Estimation of ship motions using closed-form expressions.* Ocean Engineering 31, 61-85, 2004.

9. Fonseca, N., Guedes Soares, C., *Comparison of numerical and experimental results of non-linear wave-induced vertical ship motions and loads.* Journal of Marine Science and Technology, 6:193-204, 2002.

10. Tassin, A. et al, *Assessment and comparison of several analytical models of water impact.* Inernational Journal of Multiphysics, V. 4, No. 2, 2010.

11. Temarel, P. et al, *Prediction of wave-induced loads on ships: Progress and challenges.* Ocean Engineering, V. 119, p. 274-308, 2016.