Lecture 8

Wave Loads

The evaluation of structural responses is key element in ship design. Fundamental to this is the determination of the wave loads to support the Rule requirements and for application in direct calculations (Hirdaris et al. 2014). To date, the current design philosophy for the prediction of ship motions and wave-induced loads has been driven by empirical or first-principles calculation procedures based on well-proven applications such as ship motion prediction programs employing the strip theory and panel method explained in Lecture 7. In recent years, the software, engineering and computer technology available improved dramatically. Thus a trend that may utilize the latest technologies to assess the design loads on new designs emerged. This lecture reviews some of the key methods that may be used for the assessment of wave loads on ships.

8.1 Classification of wave loads

A prime category of static loads that involve hydrodynamic actions and are frequently used in the structural analysis are still water loads. They may be attributed to (a) the variation of buoyancy distribution along ship length and (b) the non - uniform longitudinal distribution of light and dead weights (see Figure 8-1). The longitudinal uneven distribution of the net load causes vertical shear and bending moment. Still water loads may be either sagging or hogging depending on the resultant distribution of the net load.

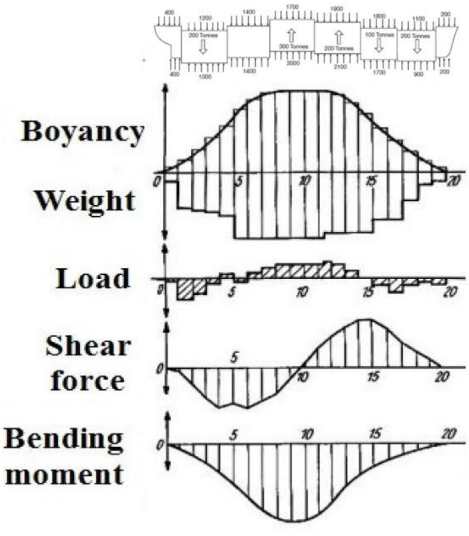

Figure 8-1: Load, shear force and bending moment diagrams (Shama 2013)

Cargo weights have the largest impact on the bending moment and shear forces as they may vary rapidly during loading, unloading and seaway operations. To avoid such risks the cargo should be spread out and interspersed, rather than grouped, as the latter distribution causes high bending moment and shear force, (see Figure 8-2). In similar fashion to vertical shear, when a ship hogs and sags shear forces shall emerge in way of her longitudinal plane. The maximum longitudinal shear force is at the neutral axis and decreases towards the deck and bottom (see Figure 8-3).

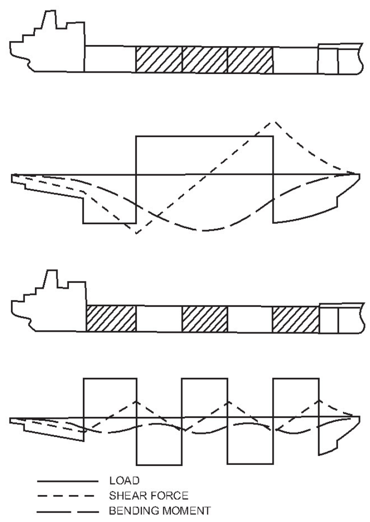

Figure 8-2 Still water shear force and bending moment for various cargo distribution (Shama 2013).

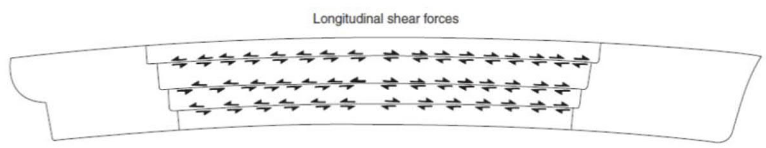

Figure 8-3 Longitudinal shear forces (Shama 2013)

Slowly varying loads are bending moments and shear forces in seaway. Waves may cause high variation in the buoyancy distribution throughout the ship length that significantly increases the bending moment and shear force. The largest effect occurs when the ship is balanced on the peak of a wave that has the same length as the ship with crest amidship. The crest at the amidship increases the amidship buoyancy forces and leads to hogging vertical bending moments. On the other hand, when the ship is on a wave trough amidship sagging vertical bending moments prevail (see Figure 8-4).

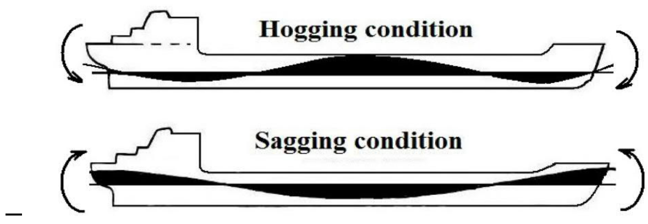

Figure 8-4 hogging and sagging condition in a regular wave

Horizontal bending around the ship's vertical axis (say the Z-axis) occurs when the ship is in an inclined condition due to rolling. This moment arises when the ship has a wave crest on one side that phases a trough on the other side in oblique or beam seas. Based on engineering experience it is noteworthy to mention that this type of moment for most small mono-hull ships is usually less than 20% of the vertical bending moment of most for large tankers and mega-containerships, it can rise to as high as 50% of the vertical bending moment. Torsion becomes important in oblique seas where the ship may be subject to opposite direction righting moments at her forward and aft parts. Ships with large deck openings, like containerships and mega bulk carriers, can experience significant torsion moments. Racking loads arise from ship rolling and they are of practical significant for shoe box type hulls, i.e. ships without transverse bulkheads (e.g., ro-ro ships car ferries) or ships without full depth transverse bulkheads at all. The deck tends to move laterally relative to the bottom, while the side shell moves vertically relative to the other side as shown in Figure 8-6.

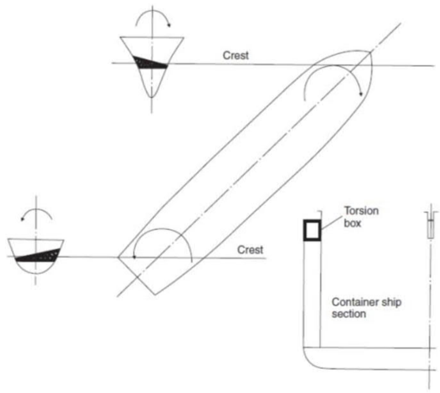

Figure 8-5 Torsion moment in oblique seas

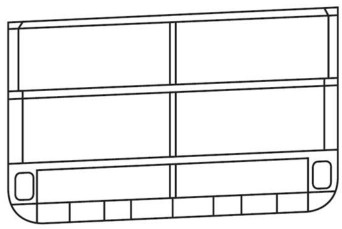

Figure 8-6: Racking deformation (Hughes, 2010)

Rapidly varying loads have short periods and require a dynamic analysis to be estimated accurately. For example, shipping of green seas on deck is an impact load that mostly affects the forecastle deck. Panting originates by the variable external water pressure from waves which causes the shell plating to bellow-in and bellow-out continually like a fashion. The pitching motion of the ship in waves highly affects this type of load. Slamming loads originate from heaving and pitching motions. During slamming events the forward vessel speed in a wave trough lead to emergence of the forward portion of the vessel. Consequently, the ship experiences a severe hydrodynamic impact on water re - entry. Slamming loads are rapid and intense and are usually accompanied by a loud booming or slamming sound. They may be critical for monohull ships with large bow flare and broad stern but also influence multihulls like catamarans (see Figure 8-7).

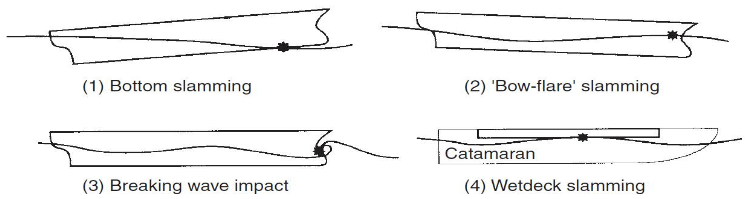

Figure 8-7 Types of ship slamming loads

8.2 Murray's method

Murray's Method can be employed to estimate the longitudinal bending moment amidships which arises when the ship is stabilized on a `Standard Wave'. Standard Wave means a wave with length equals to the length of the ship (L) and height equals $0.607\sqrt{L(\text{meter})}$, See Figure 8-8.

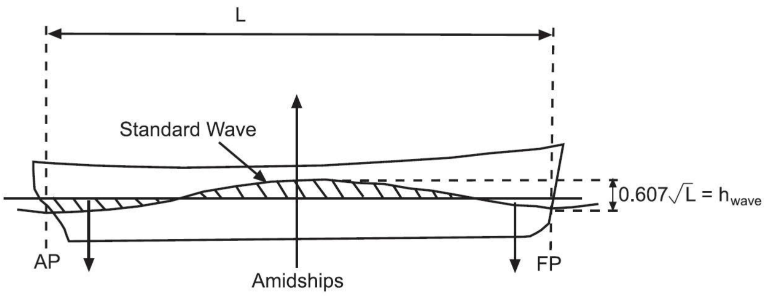

Figure 8-8 Standard wave (Barrass and Derrett 2011)

This method can be categorized as static analysis because it does not consider the dynamic load components induced by the waves. The total bending moment can be divided into two parts namely the still water bending moment and wave-induced bending moment. The wave-induced bending moment is given as a function of ship breadth (B) and Length (L) as follows:

$$M_w = b \cdot B \cdot L^{2.5} \times 10^{-3} \text{ tonnes metres} \qquad (8\text{-}1)$$

where b is a constant based on the ship block coefficient C_b and whether the ship is sagging or hogging. The values of b are given in Table 8-1.

Table 8-1 Murray's coefficient 'b'

	Values of b	
C_b	Hogging	Sagging
0.80	10.555	11.821
0.78	10.238	11.505
0.76	9.943	11.188
0.74	9.647	10.850
0.72	9.329	10.513
0.70	9.014	10.175
0.68	8.716	9.858
0.66	8.402	9.541
0.64	8.106	9.204
0.62	7.790	8.887
0.60	7.494	8.571

If the still water bending moment is not available it can be obtained using the following approximation

$$M_s = \frac{W_F + W_A}{2} - \frac{W}{2} \cdot LCB \qquad (8\text{-}2)$$

where W is the total ship weight, W_F is the moment of the weight forward of amidships and W_A is the moment of the weight aft of amidships. The first term of equation (8-2) represents the mean weight bending moment while the second term represents the mean buoyancy moment. If the mean weight moment is greater than the mean buoyancy moment at amidships the ship hogs in still water (+ve M_s) and vice versa. The total bending moment from still water and waves can be obtained by summing the still water bending moment M_s and the wave bending moment M_w when the ship sags and/or hogs. In reality, apart from the static forces acting on the body when the ship is balanced on a stationary wave, there is additional inertia component originates from the ship's motion should be added to the ship's weight distribution, while the buoyancy distribution gets more complicated. These motions generate outgoing waves causes oscillating pressures on the wetted hull surface; integrating these pressures over the wetted surface yields the forces and moments acting on the ship from waves. However, the simplification of Murray's method still can be adopted to give an indication of the maximum bending moment in waves.

8.3 Wave induced responses

The classification of wave loads into still water, slowly and rapidly varying respectively link with static, quasi-static and dynamic responses. The evaluation of static response does not consider any wave actions. In quasi-static analysis some motion effects are considered. In dynamic analysis the effects of hydrodynamic actions and time variation of loads are considered. In those cases that vibratory actions arising from waves may lead to local or global resonance phenomena associated with slamming (leading for example to whipping) or springing specialist dynamic analysis accounting for the influence of hydroelastic actions in the wave environment is recommended. Figure 8-9 illustrates the topology of responses from global hull girder to local response. The following sections provide an outline on the importance of linear and nonlinear hydrodynamic actions, flexible hull girder dynamics (i.e. hydroelasticity effects)

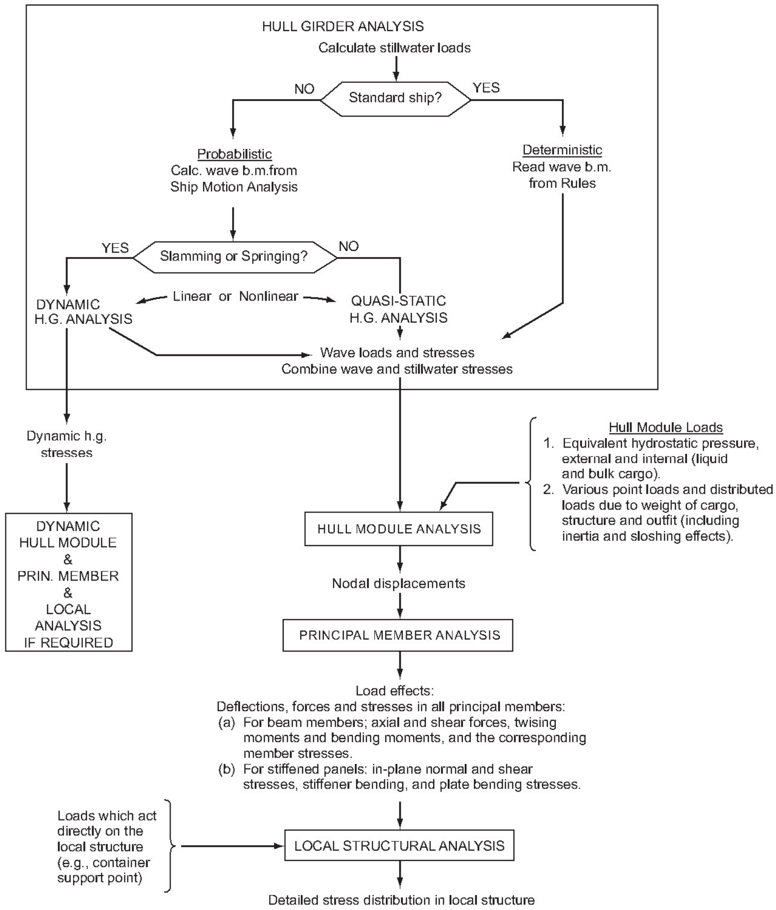

Figure 8-9 Structural response analysis

8.4 The importance of hydrodynamic actions

Global hull girder loads of large ships and ships that have unusual hull form proportions are usually nonlinear. This is because of considerable fluctuations of the waterplane below and above the waterline. Linear analysis of these loads is not 100% reliable using empirical rules and hydrodynamic analysis may be utilized to address these influences of either linear hydrodynamic actions or nonlinear effects associated with wave elevation in way of the free surface, variations of the waterplane area, forward speed effects etc. It is noted that implementation of nonlinear hydrodynamic actions can provide revised hogging and sagging correction factors to be applied in the linear analysis of the ship global loads. For illustration purposes this section demonstrates the linear and nonlinear calculation of the shear force and bending moment for the case of a ship with seakeeping coordinate system (that is the body-fixed coordinate system) illustrated in Figure 8-10.

In linear analysis, the net load $q(x)$ (force / unit length) in waves can be obtained by summing the ship weight $m(x)g$, buoyancy at each section with area $A(x)$, inertia from the heaving motion $m(x)\ddot{\eta}_3$, inertia from the pitching motion $m(x)x\ddot{\eta}_5$ and the hydrodynamic forces $F(x)$ as follows:

$$q(x) = -m(x)g + \rho g A(x) - m(x)(\ddot{\eta}_3 - x\ddot{\eta}_5) + F(x) \qquad (8\text{-}3)$$

The shear force at each section x'_p is obtained by integrating the net load throughout the ship length as illustrated in Eq. (8-4). The bending moment is evaluated by integrating the shear force along the ship length according to Eq.(8-5).

$$Q(x'_p) = \int_0^{x'p} q(x')dx' \tag{8-4}$$

$$M(x'_p) = \int_0^{x'p} x'q(x')dx' \tag{8-5}$$

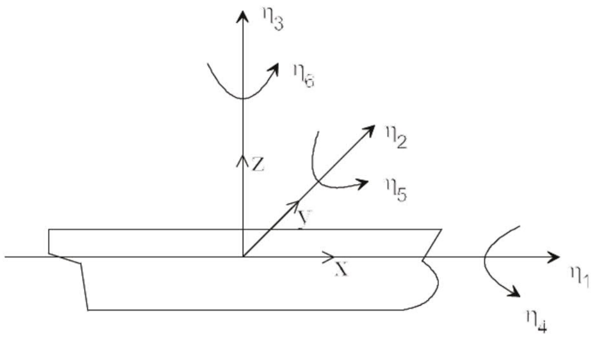

Figure 8-10 ship-fixed co-ordinate system and motion components employed in the linear and nonlinear analysis

As the model is linear, we can employ it to get the RAO of the vessel in different operating conditions (different wave heading, forward speed and loading condition). Notwithstanding it is important to note that linear assumptions do not help us distinguish between hogging and sagging induced by the waves. For example, linear assumptions have been employed by (Kukkanen 2012) to evaluate the shear force and bending moment RAOs of '*Seatech-D*' Ro-Pax vessel as illustrated in Figure 8-11. Further work at Aalto university towing tank revealed considerable amount of nonlinearity in the shear force and the bending moment RAOs obtained using different wave amplitudes 'a' (see Figure 8-12). In this figure it can be noticed that the impact of nonlinearity is more obvious at frequencies close to resonance. Further comparisons demonstrated an obvious difference in the maximum and minimum loads in sagging and hogging conditions (see Figure 8-13). It can be noticed that the bending moment is remarkably large in sagging condition. The geometry of the ship's hull and the waves generated by her forward speed have large contribution in this unsymmetry.

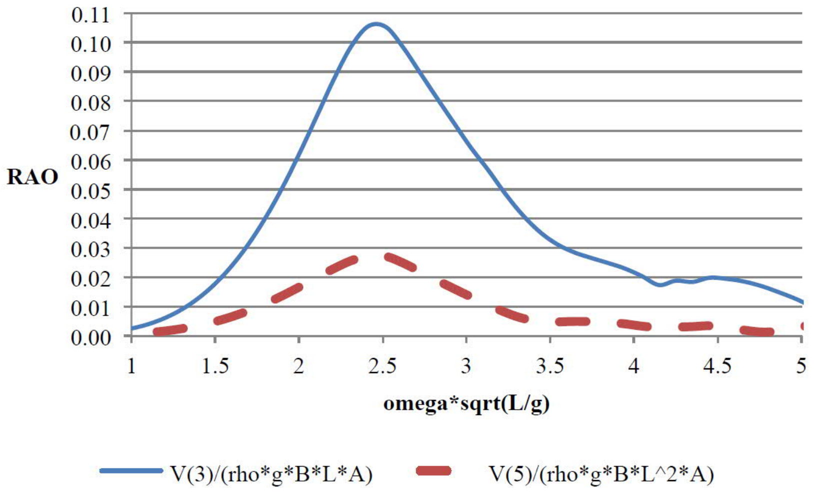

Figure 8-11 Seatech-D Ro-Pax vessel shear force and bending moment RAOs near amidships using linear theory for Fn= 0.25 in head seas (Kukkanen 2012)

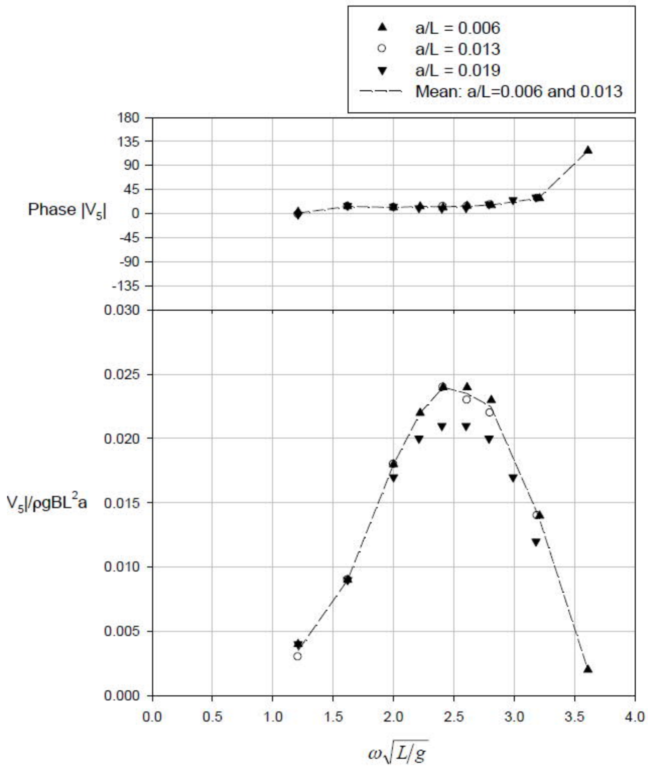

Figure 8-12 model test results of the bending moment RAO obtained using different wave amplitudes in head seas and Fn=0.25 (Kukkanen 2012).

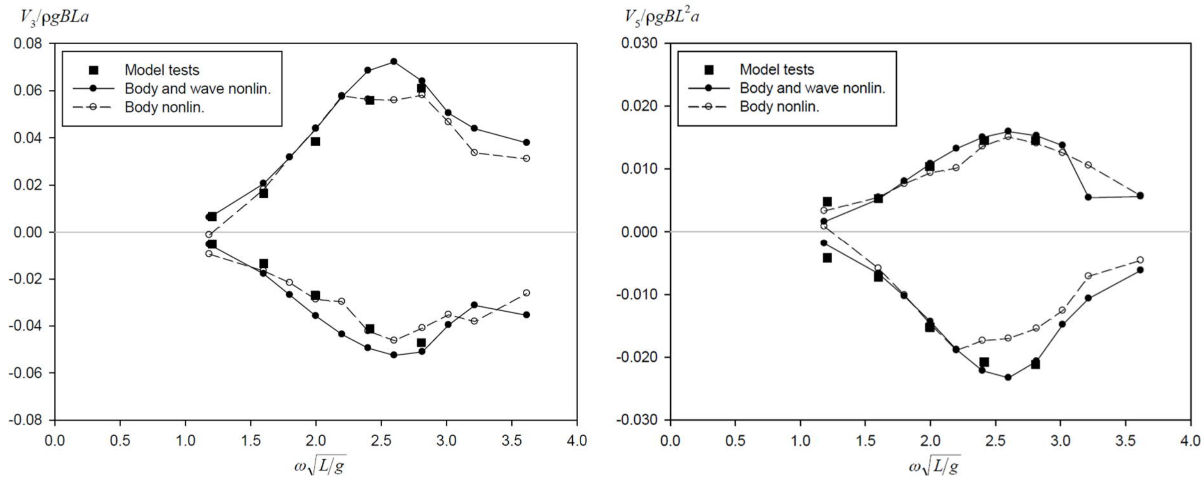

Figure 8-13 maximum and minimum loads in sagging and hogging condition (left) shear forces (right) bending moment for Fn=0 and a/L =0.013 (Kukkanen 2012).

8.5 Response in irregular waves

Wave induced dynamic loads are usually stochastic and difficult to be determined precisely. If the correlation between these loads and a ship's displacement is linear or slightly nonlinear their irregularity by aggregation of regular responses. Accordingly, the response of the structure can be solved with less effort in '*frequency domain*'. In case the correlation between the force and displacement is remarkably non-linear then the structure should be solved in the time domain with time as an independent variable. Response in waves considers the following assumptions:

- The irregularity of the ocean's waves can be represented by linear summation of a huge number of individual regular waves with different heights and periods (see Lecture 3).
- The total hydrodynamic forces are the summation hydrodynamic actions calculated on each transverse section separately (see Lectures 4-6)
- In typical analysis the ship may be considered wall sided and the wave forces acting on her may be considered linearly proportional to the wave height (linear analysis).

The accuracy of the first two of the above-mentioned assumptions are generally satisfactory. The third one gives satisfactory results for box like wall sided ships (e.g. tankers or bulk carriers) at the waterline region and can be challenged for monohull slender ships with large flare operating at moderate to high speed or multihull vessels and high speed craft. In any case, the principal steps that should be involved in stochastic analysis are summarized as follows:

- Ship seakeeping (motion response) is performed for individual regular waves with different frequencies and unit wave amplitudes. The range of frequencies used in the analysis should cover all the expected encounter wave frequencies that the ship may experience. That yields smooth definitions of the transfer function (RAO) of motions, wave-induced hull girder bending moment (or even bending stress). This analysis can be carried out using seakeeping software based on strip theory, panel method or 3D potential flow. Various commercial solvers can be used in this area of work. Examples are NAPA (https://www.napa.fi/), MAXSURF (https://maxsurf.net/), MOSES (https://bentley.ultramarine.com/), AQWA (https://www.ansys.com/products/structures/ansys-aqwa), and software developed by classification societies (e.g. BV Hydrostar - https://marine-offshore.bureauveritas.com/hydrostar-software-powerful-hydrodynamic).

- As explained in Lecture 3, the energy contained in each short-term sea state is defined by a wave spectrum $S_\eta(\omega|H_s, T_z)$ (e.g. Pierson–Moskowitz, Jonswap etc.).
- Each RAO is then used to calculate the response spectrum, $S\,(\omega|H_s, T_z, \theta)$, by scaling the wave energy spectrum as:

$$S\,(\omega|H_s, T_z, \theta) = |H\,(\omega|\theta)|^2\, S_\eta(\omega|H_s, T_z) \tag{8-6}$$

- The extreme response occurs when the peak of the wave spectrum matches the peak of the RAO. In case the sea state is represented by different wave spectra, results are combined taking into account the proportion of each spectrum on RAO.
- The above analysis is repeated for different sea states with different headings and forward speeds. Each iteration represents the short-term response, while the statistical combination of these short-term responses, based on the wave scatter diagram, represents the long-term response.
- The long-term response can be used for probability analysis of different failures limit states. For the keen reader the mathematical background and process on how to achieve this within the context of both rigid and flexible ship dynamics is explained by (Wu and Moan 2006) and (Tilander, Patey, and Hirdaris 2020).

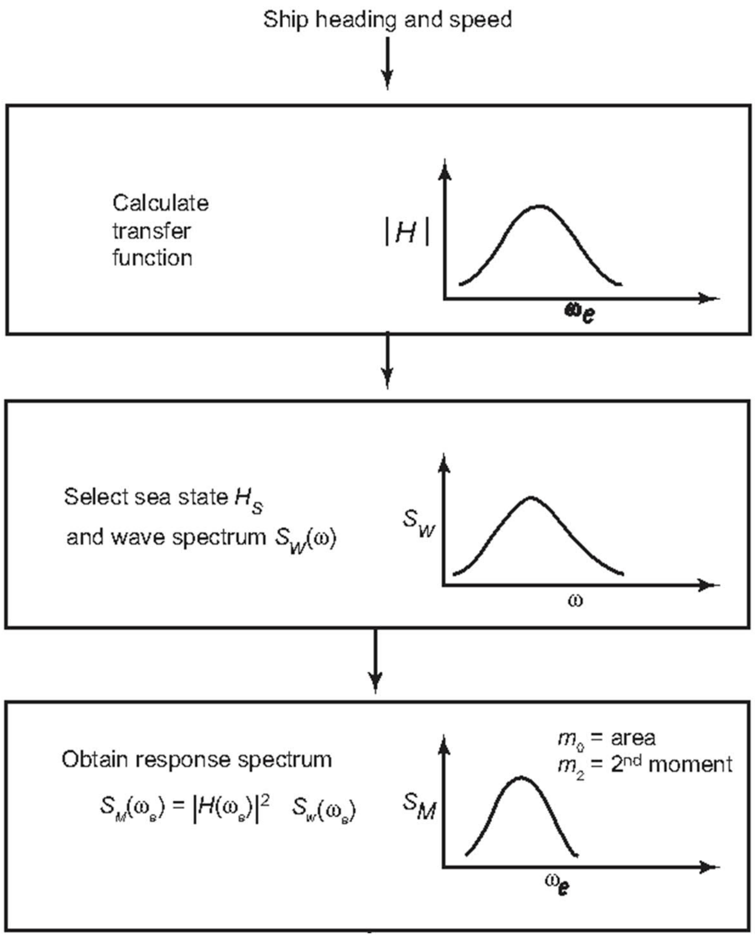

Figure 8-14 Stochastic ship dynamics (Hughes 2010)

8.6 Hydroelasticity of ships

Traditional ship dynamics assume that ships behave as rigid bodies. In reality, long slender ships are flexible structures. The influence of flexible ship hull dynamics is addressed by hydroelasticity theory; a method which assumes that ships in waves experience symmetric (i.e. vertical bending induced) and antisymmetric (coupled horizontal bending and torsion) flexible distortions. The method was introduced originally by (Bishop, Bishop, and Price 1979) and developed by various contributors to the field over the last 30 years (e.g. (Hirdaris and Temarel 2009)). When a hull experiences motions and distortions in water the resultant hydrostatic and hydrodynamic pressures influence the dynamic characteristics (e.g. natural and resonance frequencies and associated modal characteristics) of the hull. As we explained in Lecture 7 the hydrodynamic effects associated with ship seakeeping are frequency dependent. The concept of mode shapes and natural frequencies is based on time (and frequency) independent properties of the hull. This results in having to assume that the influence of the surrounding water (e.g. the added mass) is treated as frequency independent (i.e. the infinite frequency value of the added mass), in order to obtain the relevant natural frequencies and mode shapes. This is known as the wet approach. Alternatively one can consider the hull in vacuo, with the influence of the surrounding water treated as external action. This is known as the dry approach and it allows for the influence of the hydrodynamic effects to be treated as frequency dependent, as they do not contribute to the calculation of the natural frequencies and mode shapes of the dry hull. The same concept is applicable whether one uses two (2D)- or three (3D)-dimensional fluid structure interaction. In 2D linear hydroelastic analysis the dry ship hull is idealised as a beam and the fluid actions use the concept of strip theory. It is applicable to slender mono-hull vessels only as well as subject to the assumptions involved in strip theory. In 2D hydroelasticity the hull is assumed to possess port-starboard symmetry. To begin with we will focus on motions and distortions which are symmetric about the longitudinal centre plane of symmetry; hence the term symmetric. These are the heave and pitch motions (surge ignored) and the distortions associated with the vertical bending of the hull.

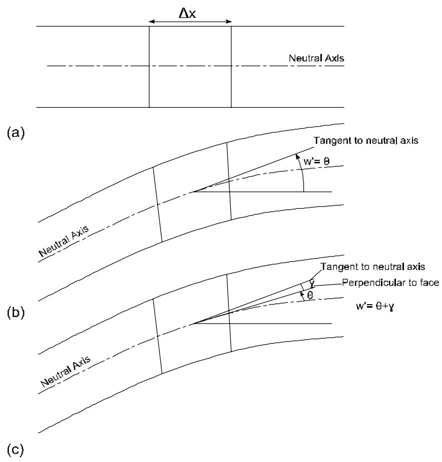

Figure 8-15 Illustration of differences between Euler and Timoshenko beams used in 2D hydroelasticity analysis; (a) undistorted beam, (b) Euler beam and (c) Timoshenko beam. Neutral axis is through the beam centroid.

The 3D form of the method was developed to include the non-beamlike structures as offshore and multihull structures. The numerical studies of the hydroelasticity employing CFD, potential flow theories and finite element methods have become common due to the wide availability of the software used in this analysis. Typically, it requires a structural finite element model and a potential flow green function model of the vessel. Further details on the significance and application of the method is included in a recent publication by (Tilander, Patey, and Hirdaris 2020). In both 2D and 3D hydroelasticity methods the analysis usually aims to investigate the vessel natural frequencies and also to get its transfer function or RAOs. Figure 8-16 indicates key results from 3D hydroelastic analysis of a container ship in regular waves using BV Hydrostar computer program. Based on this illustration it is clear that traditional hydrodynamic analysis can help evaluate the vertical bending moment RAO for low-frequency regular waves in head seas. However, it fails to capture the influence of flexible ship dynamics at higher encounter frequencies. Hydroelastic predictions have been validated by elastic/segmented model tests like the one illustrated in Figure 8-17. The recent tests focused more on the unconventional ships as VLCS and ULCS, especially to study the vertical vibration of the ship hull girder.

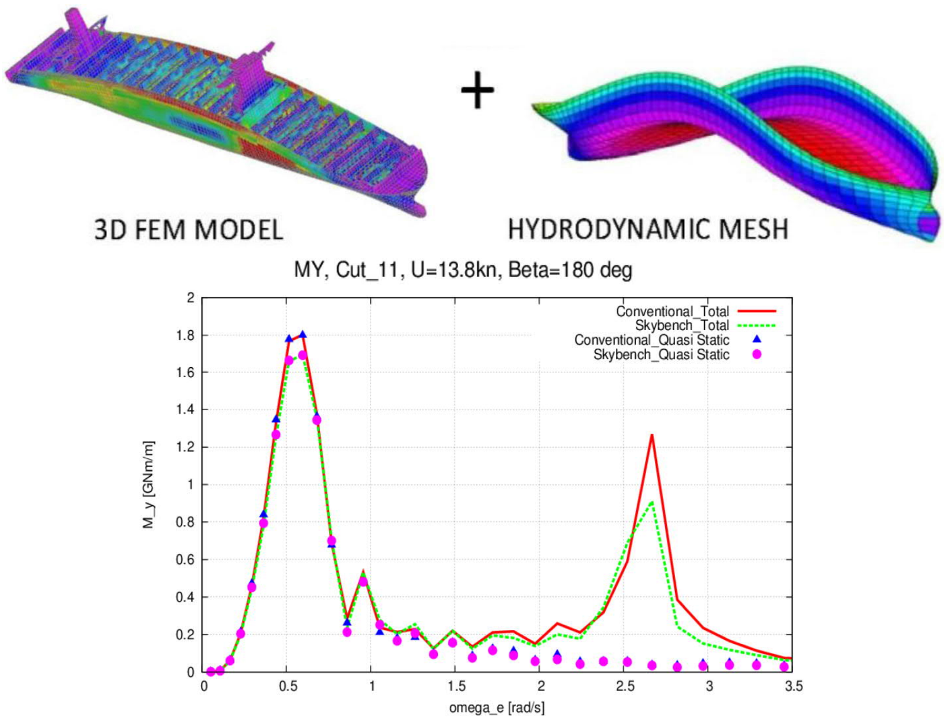

Figure 8-16 Springing analysis using BV Hydrostar software

From wave loads perspective it is notable to mention that hydroelasticity assessment focuses on the prediction of springing and whipping loads. Springing is a continual vibration (flexing) of the hull girder that may last for several hours once initiated. This phenomenon occurs when waves excite the resonant hull girder frequencies. Springing may have a great impact on vessels with high forward speed (typically above 20 knots) and low natural vibration frequencies of bending and torsional modes, usually less than 3rad/sec or 0.5 Hz. Typically, large container ships, Great Lake Carriers are more prone to springing. For the case of mega containerships their slender hull form shape and open cross sections increase their vulnerability to springing loads. On the other hand springing GLBS is associated with small moment of inertia and very high L/D ratio that decreases the natural frequency of the hull girder vertical vibration. Typically, the number of springing cycles is 4-8 times the number of wave cycles. Therefore, springing affects the fatigue strength of the structure considerably.

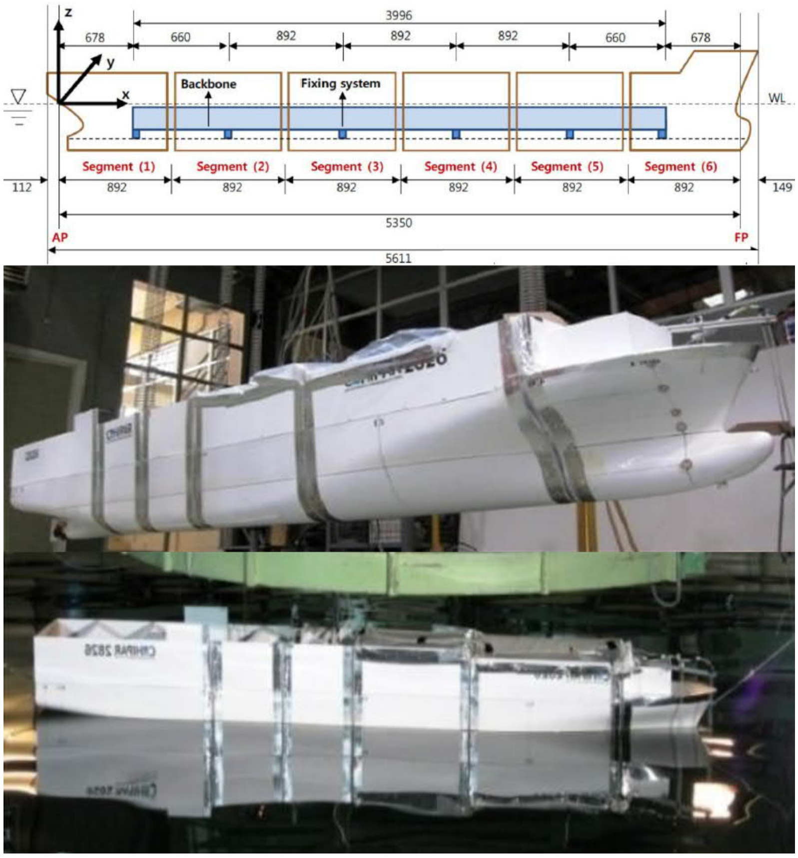

Figure 8-17 Hydroelasticity test of a segmented model of 10,000 TEU containership

Whipping induced wave loads of ships are excited by a rapid flexing of the hull girder due to wave impacts. The wave impacts emerge from bottom slamming, bow flare slamming or stern slamming and induce the propagation of high-frequency oscillations on the hull girder. The dominant oscillation mode is the vertical hull girder vibration; this mode causes a remarkable increment of the vertical bending moments and shear forces, which in consequence affects the ultimate strength of the ship. As it decays quickly and its number of cycles is usually small it is not thought to impact fatigue strength. Figure 8-18 illustrates a full-scale measurement of whipping induced vertical wave bending moment of an 8,500 TEU container ship. The whipping vibration is superimposed on the wave sagging and hogging moments and its contribution on the maximum moment is considerable.

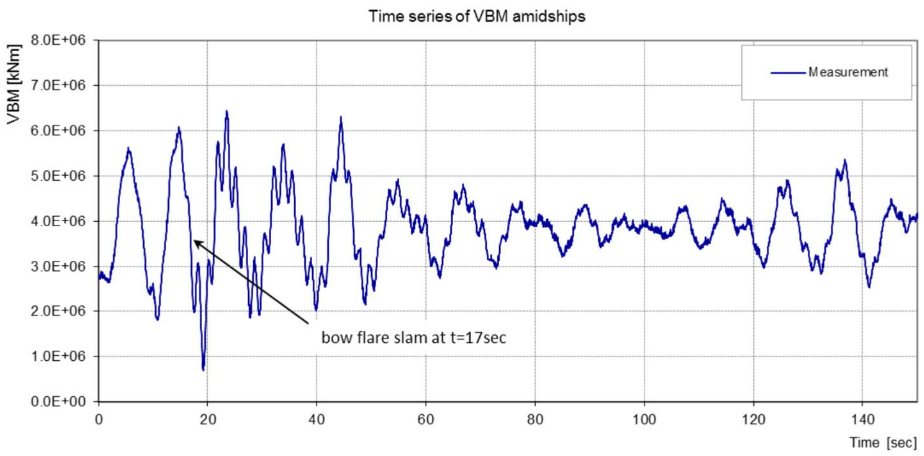

Figure 8-18 Full-scale measurements of vertical wave bending moment including whipping loads (Register January 2018)

Classification societies provide guides for the calculations of the vertical bending moment including the critical vibrational whipping loads as in equation (8-7). First, the linear bending moment M_{Linear} should be calculated and then multiplied by the whipping enhancement factor $f_{\text{f-W}}$ and the longitudinal distribution factor $f_{\text{WDA-1}}$.

$$\begin{aligned} \text{VBM}_{\text{WH-S}} &= f_{\text{fS-W}} f_{\text{WDA-1}} M_{\text{Linear}} \quad \text{for sagging} \\ \text{VBM}_{\text{WH-H}} &= f_{\text{fH-W}} f_{\text{WDA-1}} M_{\text{Linear}} \quad \text{for hogging} \end{aligned} \tag{8-7}$$

Whipping enhancement factor depends on the bow flare shape, ship length, area waterline, area amidships, critical wave frequency and the natural frequency of the 2-node hull girder vertical bending mode, given in Lloyd's Register (Register January 2018).

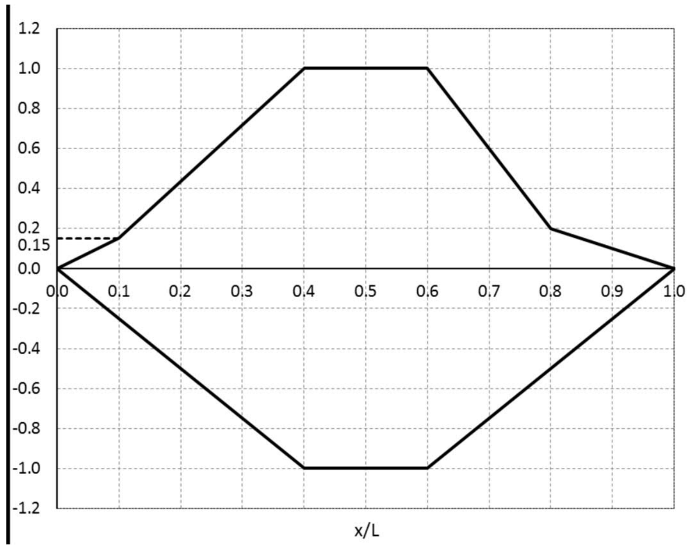

Figure 8-19 longitudinal distribution factor f_{WDA-1} (Register January 2018)

Figure 8-20 illustrates a comparison between calculated Vertical Bending Moment VBM of an 8,500 TEU container ship at amidships against full-scale measurements. The analysis is conducted in head seas, and the wave induced vertical bending moment is calculated using Jonswap wave spectrum. It can therefore be observed that the numerical results coincide well with real measurements. The oscillations in the full-scale measurement are due to the observed whipping loads. The figure shows the springing response occurs around a wave encounter frequency of 3.5 rad/sec for both real measurement and the numerical analysis. Similar numerical analysis is carried out for a passenger ship of 200 m length and 23000 tonnes displacement. The results of the vertical bending moment response as a function of encounter wave frequency are illustrated in Figure 8-21. It can be observed that the rigid body dominant response occurs at lower frequencies below 1 rad/sec. In this range the response of the ship is entirely dominated by the quasi-static analysis, assuming the ship performs like a rigid body. In contrast, the elastic behavior of the ship in very high encounter wave frequencies is vital for the springing analysis. The elastic response analysis of the considered passenger ship shows three beaks due to springing, these beaks occur between frequencies 8-12 rad/sec.

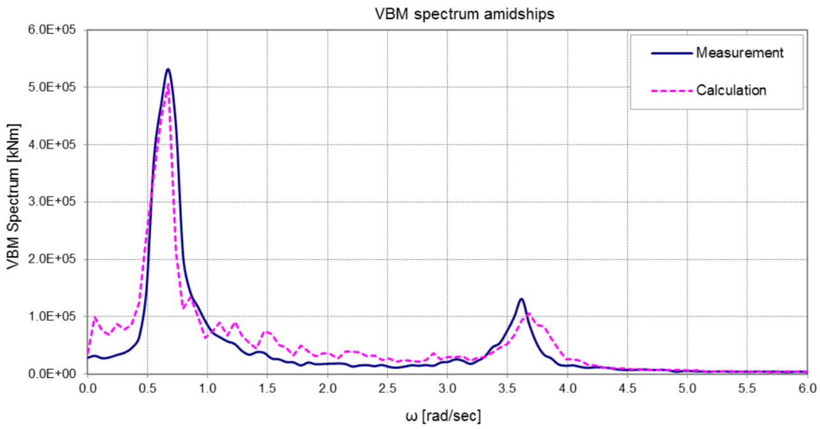

Figure 8-20 Calibration of the numerically calculated vertical bending moment using Jonswap wave spectrum against full-scale measurements (Lloyd's Register, 2018).

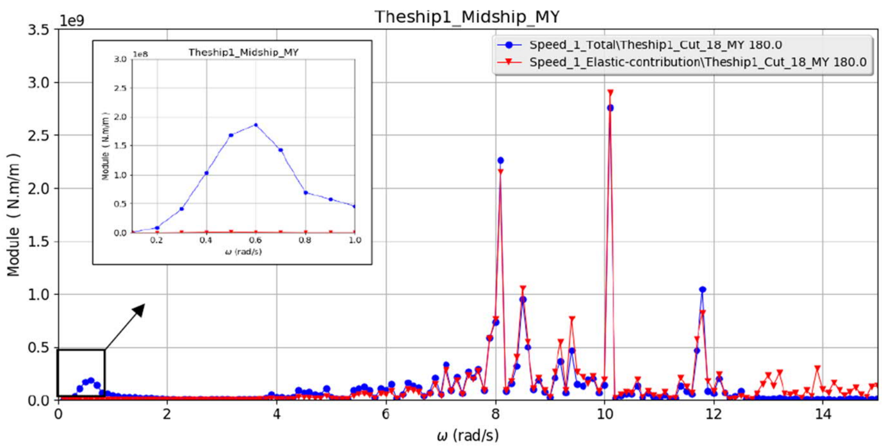

Figure 8-21 Vertical bending moment at amidship of 200 m passenger ship (Tilander, Patey, and Hirdaris 2020)

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