Guidance for Classification and Construction

Part 1 Seagoing Ships

GUIDANCE FOR DESIGN WAVE LOAD ON SHIP STRUCTURES

Volume AA

2023 Edition

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Foreword

This Guidance for Design Wave Loads on Ship Structures (Pt.1, Vol.AA) is prepared with the intent of giving details as to the treatment of the various provisions for items not specified in the Rules for Bulk Carrier and Oil Tanker (Pt.1, Vol.XVII) and Rules for Hull (Pt.1, Vol.II). This Guidance also can be applied to giving calculation procedures to IACS Rec. No. 34.

This Guidance provide methods, procedures and technical requirements as basis for classification which consist of four Sections namely:

– Section 1 – Introduction
– Section 2 – Ship Responses in Irregular Waves
– Section 3 – Linear Wave Statistics
– Section 4 – Procedure for Wave Load Analysis

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Section 1 Introduction

A. General

1. This Guidance describes methods for the calculation of the wave loads on seagoing ships, including ships with rule length **L** ≥ 350 m.

2. This Guidance is based on the principles of marine hydrodynamics and the following assumptions which are broadly acceptable in the international literature and whose adoption is necessary for the simplification of the ship-wave interaction problem:

– The sea water is considered as inviscid and incompressible fluid.
– The flow around the ship is considered irrotational.
– The equations of ship motions are linearized.
– The ocean waves are considered as an ergodic and stationary stochastic process.

3. The Guidance provide the calculation method of the ship responses (including pressures and wave loads) in both, regular and irregular waves. For the case of irregular waves, the short-term and the long-term responses are produced, the latter being necessary for ship-design purposes.

B. Scope

1. General

1.1 The formulae currently in use by major the classification societies for the calculation of the wave loads are the result of a variety of statistical analyses of theoretical and experimental studies and full-scale measurements, and they have been proven adequate for ships having a length less than 350 m. For ships of length greater than 350 m the use of the conventional calculation of applied wave loads needs additional verification due to the lack of adequate accumulated experience for this size of vessels.

1.2 This Guidance accommodate Rules for Bulk Carrier and Oil Tanker (Pt. 1, Vol. XVII) Volume XVII.B Pt. 1, Ch. 1, Sec. 2.3.2 for ships having a length over 350 m. In this case, BKI have its own guidance for the calculation of the wave loads, instead of using the prescriptive Rules which is only applicable to ships with length less than 350 m.

1.3 The ship responses in a real sea state is a stochastic process and the probability theory is a power tool to assess design values of ship motions and the associated wave-induced loads. In the context of the ship design process, values of wave loads that have a specified pre-defined probability of non-exceedance during the ship's lifetime, are required. For linear wave induced responses, theoretical methods to estimate short- and long-term probability distributions are well established. For nonlinear response, it is difficult to obtain sufficiently accurate extreme value estimates. However, the extreme nonlinear response is usually related in time to the extreme linear response. In this aspect, linear approach will be also adopted in this Guidance.

2. Application

This Guidance applies for directly calculated hydrodynamic wave loads and ship motions for the following, but not limited to:

- ships;
- linear and non-linear wave induced response;
- unlimited service, i.e. North Atlantic;
- restricted service with a specific scatter diagram;
- hull forms within the limitations given in the Rules for Hull (Pt.1, Vol.II) Sec. 5, B.1.1;
- hull forms outside the limitations given in the Rules for Hull (Pt.1, Vol.II) Sec. 5, B.1.1 and Rules for Bulk Carrier and Oil Tanker (Pt. 1, Vol. XVII.B) Part 1, Chapter 1, Section 2.3.2;
- calculation procedures according to IACS Rec. No. 34

C. Definitions

For the sake of clarity and for the better understanding of this guidance, following definitions are given:

Dispersion relation : the relationship between the wave period T [s], and the wave length λ [m]. This relation depends on the water depth d [m].

Group velocity (C_g) : the speed of wave energy transfer, i.e. the speed of the wave front in a wave train [m/s], i.e. the speed of the moving wave train, being less than the speed of the phase velocity.

Non-linear regular waves (irregular waves) : asymmetric waves, A_C (crest height) > A_T (trough height), where the phase velocity. depends on wave height, i.e. the dispersion relation is a functional relationship between T, λ and H.

Peak period (T_p) : the wave period or the period of another response like vertical bending moment [s], with most energy in the wave or response spectrum, i.e. the most probable maximum wave or response in a short term sea state.

Phase velocity (c) : the propagation velocity of the wave form and denoted by $c = \frac{\lambda}{T}$ [m/s].

Probability density function (pdf) : a function pdf(x) showing the probability of occurrence at different levels of the parameter x, which could be any parameter. Integrated it will give the probability within ranges of x.

Regular wave : assumed to be sinusoidal with constanta wave amplitude, wavelength, and wave period, described by the ideal fluid potential flow.

Significant wave height (H_s) : the average wave height, from trough to crest, of the highest one-third of the waves [m].

Short term sea state : a sea state characterised by a wave spectrum, H_s and T_z (or T_p) and with a duration in order of 3 hours.

Surface elevation {η(x,y,t) [m]} : the distance between the still water level and the instant wave surface elevation at location (x,y) at time t.

Wave amplitude (A) : called the distance of a wave crest or wave trough from the still water surface [m]

Wave period (T) : the time interval between successive crests of a wave sequences [s].

Wave crest height (A_C) : the distance from the still water level to the wave crest [m].

Wave height (H) : between the crest and trought within the wave period [m].

Wave trough depth (A_T) : the distance from the still water level to the trough [m].

Wave frequency (f) : the inverse of the wave period, $f = \frac{1}{T}$ [s^{-1}].

Wave angular frequency (ω) : the angular frequency given by the relation: $\omega = \frac{2\pi}{T}$ [rad/s].

Wave length (λ) : the distance between two successive crests or troughs [m].

Wave number (k) : mathematically expressed as the number of the complete cycle of a wave over its wavelength, defined as the ratio $\frac{2\pi}{\lambda}$ [rad/m].

Zero-up-crossing period (T_z) : the wave or response period [s], between two up-crossings of the zero level in a specific wave/response event or average based on a short term sea state or long term statistics.

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Section 2 Ship Responses in Irregular Waves

A. Introduction

This Section describes ship responses in irregular waves which depend on wave conditions (see B.) to determine Response Amplitude Operators (RAO) of the six degrees of freedom motion to calculate ship's response (see C.) with respective wave spectrum.

B. Wave Conditions

1. General

In a sea state, the wave induced response depends on the specific encountered wave event characterized by e.g. a wave height and a wave period. Short term response is a statistical representation of the wave induced response in a sea state, which is defined by a wave spectrum and wave energy spreading. Long term response is based on a statistical representation of all encountered sea states defined by a scatter diagram. These wave conditions are described and are necessary input to calculation of wave induced response.

2. Regular Waves

A regular travelling wave is propagating with permanent shape and parameters as illustrated in Fig. 2.1. Relevant parameters are:

– wave length, λ [m]
– wave period, T [s]
– phase velocity, c [m/s]
– wave frequency, f [1/s]
– wave frequency, ω [rad/s]
– wave number, k [rad/m]
– surface elevation, η [m]
– wave crest height, A_c [m]
– wave trough depth, A_T [m]
– wave height, H [m]
– dispersion relation
– wave crest speed, λ/T [m/s]
– wave group velocity, C_g [m/s]
– wave steepness, H/ λ

The wave steepness in deep water, S, is defined as:

$$S = 2\pi \frac{H}{g \cdot T^2} = \frac{H}{\lambda}$$

The maximum wave height H_{max} to wave length λ ratio (maximum steepness) defining the wave breaking limit depends on the wave length and the water depth, d [m]. The maximum steepness is given by:

$$\frac{H_{max}}{\lambda} = 0{,}142 \cdot \tanh \frac{2 \cdot \pi \cdot d}{\lambda}$$

In deep water, the breaking wave limit corresponds to a maximum steepness, S_{max}:

$$S_{max} = \frac{H_{max}}{\lambda} = \frac{1}{7}$$

In shallow water the limit of the wave height can be taken as 0,78 times the local water depth. The dispersion relation in deep water can be written as:

$$\omega^2 = k \cdot g$$

Based on this, the wave length in m, may be calculated as:

$$\lambda = \frac{2}{2\pi} T^2 = 1{,}567\, T^2 \qquad [m]$$

The phase velocity or wave speed of the propagating crest, c [m/s], can be estimated as:

$$c = \frac{\lambda}{T} = \frac{\frac{g}{2\pi} T^2}{T} = \frac{gT}{2\pi} = 1{,}567\, T \qquad [m/s]$$

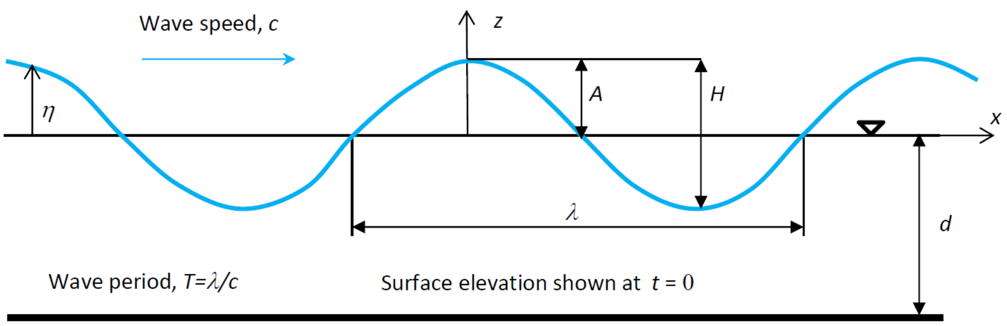

Fig. 2.1 Regular travelling wave properties

3. Scatter Diagram

3.1 A standard scatter diagram defines the probability of occurrence of the different sea states. Each sea state is defined by the significant wave height, H_s [m] and the mean wave period, T_{0m1} [s] (or peak period T_p [s]). The North Atlantic scatter diagram is given in Table 2.1.

Table 2.1 Scatter diagram for North Atlantic operation with H_s [m] and T_{0m1} [s]

Significant wave height, Hs (m)	Mean wave period, T_{0m1} (s)																Sum
	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	
0.5	6.82	202.00	333.61	187.76	45.59	4.74	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	780.73
1.5	0.33	2028.35	12750.82	11693.39	7215.76	3006.80	846.07	160.77	20.63	1.79	0.10	0.00	0.00	0.00	0.00	0.00	37724.81
2.5	0.00	3.38	2805.81	8517.74	7835.85	5885.37	3608.30	1805.81	737.71	246.00	66.96	14.88	2.70	0.40	0.05	0.00	31530.96
3.5	0.00	0.00	23.06	2742.51	4666.81	4100.83	2936.41	1713.38	814.68	315.65	99.66	25.64	5.38	0.92	0.13	0.01	17445.07
4.5	0.00	0.00	0.00	82.06	1759.81	2069.19	1715.42	1151.29	625.51	275.12	97.96	28.24	6.59	1.24	0.19	0.02	7812.64
5.5	0.00	0.00	0.00	0.08	149.74	811.81	791.81	609.66	375.67	185.26	73.12	23.09	5.84	1.18	0.19	0.02	3027.47
6.5	0.00	0.00	0.00	0.00	1.02	147.59	305.37	271.71	190.23	104.79	45.42	15.49	4.16	0.88	0.15	0.02	1086.83
7.5	0.00	0.00	0.00	0.00	0.00	4.77	88.62	107.20	86.26	53.35	25.36	9.27	2.60	0.56	0.09	0.01	378.09
8.5	0.00	0.00	0.00	0.00	0.00	0.02	9.40	38.70	36.80	25.95	13.63	5.33	1.55	0.34	0.05	0.01	131.78
9.5	0.00	0.00	0.00	0.00	0.00	0.00	0.20	9.34	15.15	12.51	7.39	3.12	0.94	0.20	0.03	0.00	48.88
10.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.81	5.73	5.96	4.08	1.90	0.60	0.13	0.02	0.00	19.23
11.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	1.29	2.68	2.23	1.18	0.40	0.08	0.01	0.00	7.89
12.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	1.01	1.14	0.72	0.27	0.06	0.01	0.00	3.32
13.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.51	0.42	0.18	0.04	0.00	0.00	1.37
14.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.19	0.21	0.12	0.03	0.00	0.00	0.57
15.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.09	0.07	0.02	0.00	0.00	0.22
16.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.04	0.01	0.00	0.00	0.08
17.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.00	0.00	0.04
18.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.02
Sum	7.15	2233.73	15913.30	23223.54	21674.58	16031.12	10301.81	5868.69	2909.77	1230.31	437.79	129.62	31.47	6.11	0.92	0.09	100000.00

These wave scatter diagrams are based on the North Atlantic by wave data source illustrated in Fig. 2.2 as described in IACS Rec. 34. The relationship between the mean wave period, T_{0m1} in the scatter diagram in Table 2.1 and the peak wave period can be evaluated by the following equation:

$$T_{0m1} = \left(0{,}7757 + 0{,}0965\sqrt{\gamma} - 0{,}0144 \cdot \gamma\right) \cdot T_p$$

The H_s and T_{0m1} values are class midpoints. $T_{0m1} = 2\pi \frac{m_{-1}}{m_0}$, where is the spectral moment of order n.

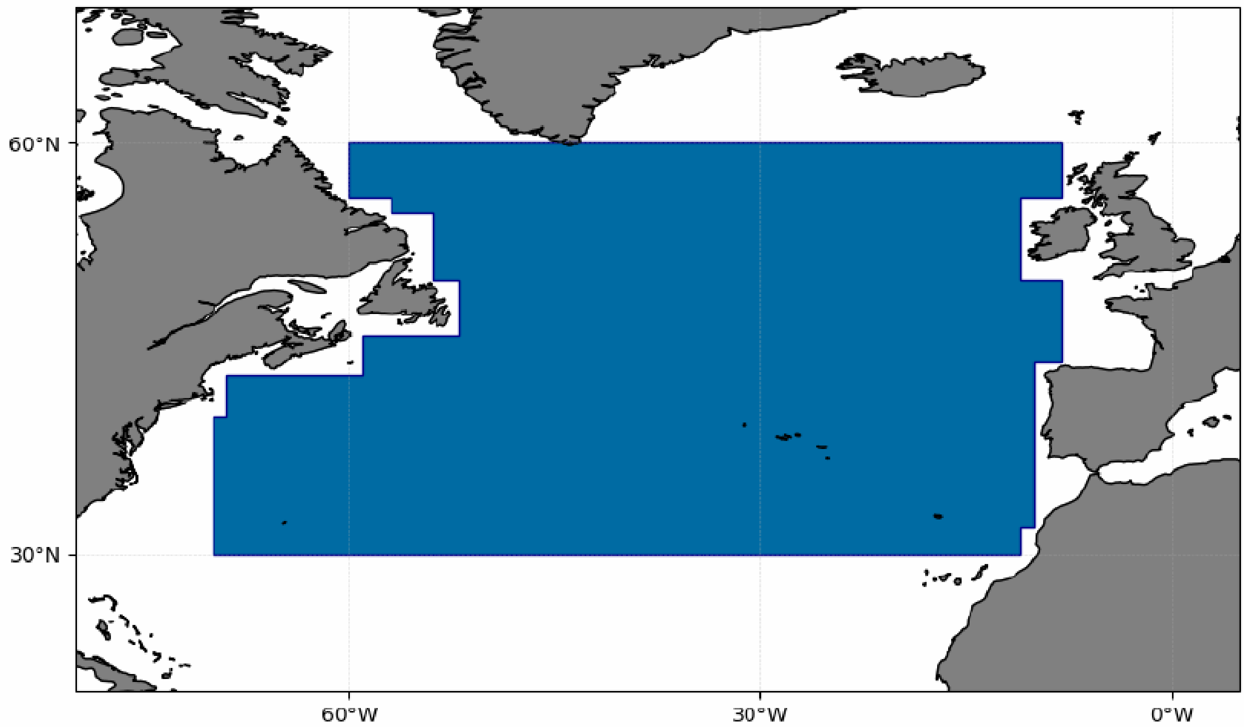

Fig. 2.2 Definition of the extent of the North Atlantic

3.2 According to IMO GBS FR I.1, the specified ship design life is at least 25 years. This life span determines the number of cycles of the ship response to waves which in turn determines the probability of response exceedance per cycle. It is assumed in the numerical model determining the long-term ship responses to waves that the probability of exceeding the design value of ship response to waves is 10^{-8}, which approximately corresponds to 25 years of the specified ship design life.

4. Wave Spectrum

In an actual sea state, the wave induced response depends on the specific encountered wave system which is statistically characterized by e.g. a wave height and a wave period. Short term response is a statistical representation of the wave induced response during a specific sea state, which is defined by a wave spectrum and wave energy spreading function. Long term response is based on a statistical representation of all encountered sea states defined by a scatter diagram. These wave conditions are described in the following, and constitute necessary input to calculation of wave induced response.

A wave spectrum represents the wave energy (or wave amplitude) distribution of individual wave frequencies in a stationary sea state.

A large set of standardized wave spectra are provided in Rules for Structures (Pt.5, Vol.II) Sec. 1, D including recommended parameters. Wave spectra most relevant for ships are the two-parameter Pierson-Moskowitz (PM) (i.e. Bretschneider) and JONSWAP wave spectra. These are unidirectional wave spectra referred to as single peak one-dimensional wave spectra, i.e. without wave energy spreading.

The PM wave spectrum for fully developed sea is given by:

$$S_{PM}(\omega) = \frac{5}{16} \cdot H_s^2 \omega_p^4 \cdot \omega^{-5} \exp\left[-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right]$$

where:

H_s	=	the significant wave height [m]
ω	=	wave frequency [rad/s]
ω_p	=	spectral peak frequency [rad/s]
	=	$2\pi/T_p$ [rad/s]
T_p	=	peak period, in 6.

The JONSWAP wave spectrum is formulated as a modification of the PM wave spectrum, and JONSWAP represents a developing sea state in a fetch limited situation:

$$S_J(\omega) = A_\gamma \cdot S_{PM}(\omega) \cdot \gamma^{\exp\left[-0{,}5\left(\frac{\omega-\omega_p}{\sigma \cdot \omega_p}\right)^2\right]}$$

where:

γ	=	non-dimensional peak shape parameter
σ	=	spectral width parameter
		σ_a for $\omega \le \omega_p$
		σ_b for $\omega > \omega_p$
A_γ	=	1-0,287 ln(γ) is a normalizing factor

Average values for the JONSWAP experimental data as IACS Rec. 34 are γ =1,5, σ_a = 0,07, σ_b = 0,09.

For γ = 1, the JONSWAP wave spectrum reduces to the PM wave spectrum.

The JONSWAP wave spectrum is expected to be a reasonable model for:

$$3{,}6 < \frac{T_p}{\sqrt{H_s}} < 5$$

and should be used with caution outside this interval. The effect of the peak shape parameter, γ, is shown in Fig. 2.3.

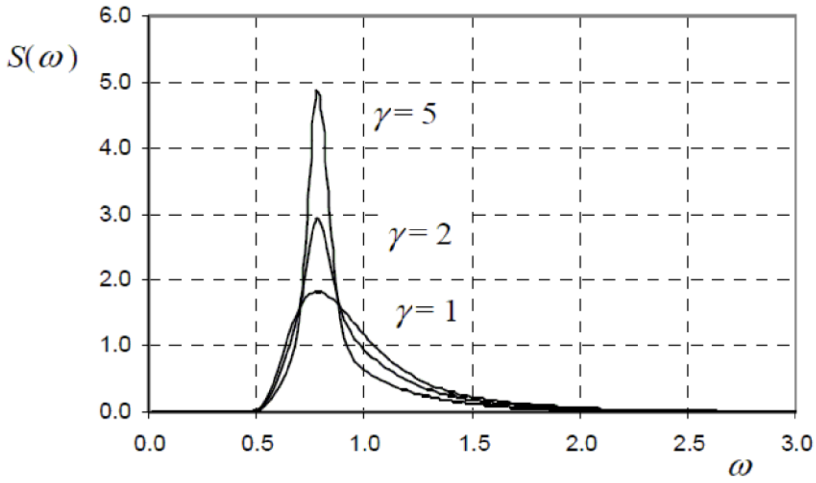

Fig. 2.3 JONSWAP spectrum for H_s = 4.0 m, T_p = 8.0 s and for γ = 1, 2 and 5.

If no particular values are given for the peak shape parameter, γ, the following value may be applied:

$$\gamma = 5 \qquad \text{for} \quad \frac{T_p}{\sqrt{H_s}} \le 3{,}6$$

$$\gamma = \exp\left[5{,}75 - 1{,}15\frac{T_p}{\sqrt{H_s}}\right] \qquad \text{for} \quad 3{,}6 < \frac{T_p}{\sqrt{H_s}} < 5$$

$$\gamma = 1 \qquad \text{for} \quad \frac{T_p}{\sqrt{H_s}} \ge 5$$

Both JONSWAP and PM wave spectra adopt ω^{-5} as the governing high frequency tail behaviour. There is empirical support for a tail shape closer to the theoretical shape ω^{-4}. The difference between ω^{-4} and ω^{-5} tail behaviour may be of importance for structural dynamic response of ships, e.g. linear and non-linear springing.

4.1 Measured and simulated spectra

Wave spectra may be available from hind cast data or measured by a directional wave radar. Often these data are represented by two-dimensional frequency-heading tables of spectral values, i.e. they include directional and frequency information of the sea state simultaneously. Such data can be applied in seakeeping assessments similar to usage of standardized parameterized wave spectra. To achieve unidirectional spectrum, the wave energy over the headings needs to be integrated. Information about bi-directional wind and swell sea is then lost. The multi-peak behaviour may however be kept.

5. Wave energy spreading

The wave energy spreading describes how the wave energy is distributed over different headings relative to the main heading. A large spreading implies that the waves are short crested, while a narrow spreading implies that the waves are long crested or unidirectional.

Directional short-crested wave spectra $S(\omega,\beta)$ may be expressed in terms of the unidirectional wave spectra as:

$$S(\omega,\beta) = S(\omega) \cdot D(\beta,\omega) = S(\omega) \cdot D(\beta)$$

Where the latter equality represents a simplification often used in practice. Here $D(\beta,\omega)$ and $D(\beta)$ are directional functions. β is the angle between the direction of elementary wave trains and the main wave direction of the short crested wave system. The directional function fulfils the requirement:

$$\int_{\beta} D(\beta,\omega)\, d\beta = 1$$

For a two-peak spectrum expressed as a sum of a swell component and a wind-sea component, the total directional frequency spectrum $S(\omega,\beta)$ can be expressed as:

$$S(\omega,\beta) = S_{windsea}(\omega)\cdot D_{windsea}(\beta) + S_{swell}(\omega)\cdot D_{swell}(\beta)$$

A directional function often used for wind sea is:

$$D(\beta) = \frac{\Gamma(1+n/2)}{\sqrt{\pi}\cdot\Gamma(1/2+n/2)} \cdot \cos^{n}(\beta-\beta_p)$$

where:

Γ	=	the Gamma function
$[\beta-\beta_p]$	=	relative angle $\le \pi/2$
β	=	relative spreading around the main direction
β_p	=	main direction, which may be set to the prevailing wind direction if directional wave data are not available.

The wave induced response may be sensitive to the wave energy spreading, i.e. the constant n, which should be chosen to be representative for the actual sea state. Values representative for wind sea are $n = 2$ to 4, while for swell $n > 7$ is more appropriate. Higher sea states may also be associated with a higher n.

6. Zero up-crossing period, T_z and peak period T_p

The T_z [s] and the mean wave period T_1 [s], may be related to the peak period by the following approximate relations ($1 \le \gamma < 7$) based on JONSWAP:

$$\frac{T_z}{T_p} = 0{,}6673 + 0{,}05037\,\gamma - 0{,}006230\,\gamma^2 - 0{,}0003341\,\gamma^3$$

$$\frac{T_1}{T_p} = 0{,}7303 + 0{,}04936\,\gamma - 0{,}006556\,\gamma^2 - 0{,}0003610\,\gamma^3$$

Combining these two equations give the following relations:

For $\gamma = 3{,}3$; $T_p = 1{,}286\ T_z$ and $T_1 = 1{,}073\ T_z$

For $\gamma = 1$; $T_p = 1{,}405\ T_z$ and $T_1 = 1{,}087\ T_z$

An alternative is to estimate the zero up-crossing period, T_z, and mean wave period, T_1, directly from the spectral density function and its moments. ω_p corresponds to the highest peak in the spectral density function representing the wave spectrum, e.g. as seen in Fig. 2.3. From this the peak period can be estimated:

$$T_p = \frac{2\pi}{\omega_p} \qquad [s]$$

The spectral moments of order n of the response process for a given heading may be described as:

$$m_n = \int \omega \sum_{\beta_p - 90°}^{\beta_p + 90°} D(\beta(\cdot \omega^n \cdot S(\omega(\omega_s, T_z\beta) d\omega$$

and the zero up-crossing period and mean period are is defined as:

$$T_z = 2\pi \sqrt{\frac{m_0}{m_2}} \qquad [s]$$

$$T_1 = 2\pi \sqrt{\frac{m_0}{m_1}} \qquad [s]$$

C. Ships Response

1. General

The ship response analysis is mainly aimed to determine Response Amplitude Operators (RAO) of the six degrees of freedom motion, presenting the ship response on the wave of unit amplitude as a function of wave frequency. The ship response spectra on waves were obtained by multiplying RAO with the environmental wave spectrum.

2. Equations of Motions

2.1 Ship motions follow Newton's 2nd law:

$$\left(M + A(x)\right)\ddot{x} + B(x,\dot{x})\dot{x} + C(x)x = F(x,\dot{x},t)$$

The radiation forces, F_{rad}, takes the form:

$$F_{rad}(\ddot{x},\dot{x},x,t) = -A(x)\ddot{x} - B(x,\dot{x})\dot{x}$$

where:

M = mass matrix in air

A = added mass coefficients

B = damping coefficients

F = Excitation force

C = restoring matrix

Where the vector x denotes the ship responses, e.g. representing the 6 DOF rigid body motions. The vector F represents the excitation forces from the incident undisturbed waves (Froude-Krylov force) and diffracted (reflected) waves. The excitation forces depends on the wave encounter frequencies.

2.1.1 Radiation represent the situation when the ship generates waves going away from the ship. The mass matrix, M, represents the inertia of the ship in air. In most formulations the restoring matrix, C, is due to hydrostatics only.

2.1.2 The added mass and damping are frequency dependent. For low and high frequencies the linear damping associated with wave generation goes towards zero. The damping can also be proportional to the speed squared. It is then mainly related to viscous effects such as skin friction and vortex shedding. An important example is roll damping due to bilge keels. At high speed also hull lift damping can contribute.

2.1.3 For low frequencies the added mass goes towards zero, but at high frequencies it tends to approach a constant value. Added mass is associated with pressure being proportional to acceleration.

2.1.4 The restoring is independent of frequency and is related to the water plane area. It acts like a spring stiffness in case of changed buoyancy. It can be nonlinear in case of non-vertical ship sides and large motions and roll/pitch angles.

2.2 Consider a ship advancing at a steady mean forward speed, v, in a train of regular waves of small amplitude moving in six degrees of freedom. The angle β measured between the direction of v and the direction of wave propagation, defines the ship's heading (β = 180° corresponds to head seas). It is assumed that both the wave excitation forces and the resultant oscillatory motions are linear and harmonic, acting at the frequency of encounter, i.e, expressed as follows:

$$\omega_e = \omega - \frac{\omega^2}{g} v_o \cos\beta \qquad \text{[rad/s]}$$

where:

v_0 = ship forward speed [m/s]

β = relative heading [°] between the ship and the wave propagation direction, β = 0° in following seas

ω_0 = the circular frequency of the incident waves [rad/s]

g = the acceleration of gravity [m/s^2]

In beam seas the encounter period corresponds to the wave period. In following sea the ship speed, which cause zero encounter frequency, can be estimated as:

$$v_0 = \sqrt{\frac{g \cdot \lambda}{2\pi}} = 1{,}25\sqrt{\lambda} \quad \text{[m/s]}$$

For higher speeds the ship is overtaking the waves.

The equation of motion above without the right hand side refers to free motion. In this case the natural frequency can be estimated neglecting the damping. The natural frequency, ω_n [rad/s], is expressed as:

$$\omega_n = 2\pi\sqrt{\frac{C}{M+A}} \qquad \text{[rad/s]}$$

The natural period [s], is the inverse relation of the natural frequency:

$$T_n = \frac{2\pi}{\omega_n} \quad [s]$$

2.3 For the computation of all responses of any vessel to regular waves, it is necessary to deal with the complete motions of a ship with six degrees of freedom, considering important couplings among them. The linear equations will be presented for a ship advancing at constant mean forward speed with arbitrary heading in a train of regular sinusoidal waves.

3. Irregular waves

Regular waves are sinusoidal waves as illustrated in Fig. 2.1. The surface propagation, η(x,t) [m], can be written as:

$$\eta(x,t) = A\cos(\omega t - kx)$$

Where:

A	=	wave amplitude [m]
ω	=	wave frequency [rad/s]
k	=	wave number [rad/m]
	=	2π/λ [rad/m]

Irregular waves representing a sea state can be expressed as a linear summation of regular wave components, i:

$$\eta(x,t) = \sum_{i=1}^{n} A_i \cos(\omega_i t - k_i x + \varepsilon_i)$$

Where:

ε_i	=	random phase variable evenly distributed between 0 and 2π.

The amplitude A_i can be estimated from the wave spectrum S(ω) described in B.4:

$$\eta(x,t) = \sum_{i=1}^{n} A_i \cos(\omega_i t - k_i x + \varepsilon_i)$$

where:

$\Delta\omega_I$	=	Frequency interval considered [rad/s].

The maximum wave steepness of regular waves is defined in B.2. In irregular sea states, the significant wave steepness, S_S, can be estimated as:

$$S_S = \frac{2\pi}{g}\frac{H_S}{T_z^2} = \frac{2}{\pi g}\frac{m_2}{\sqrt{m_0}}$$

where:

m_0, m_2	=	zeroth and second spectral moment, see B.5

Hs = significant wave height [m]

$= 4\sqrt{m_0}$ [m]

T_z = zero up-crossing period [s], see B.5

The limiting steepness values may be taken as:

$S_S = 1/10$ for $T_z \leq 6$ [s]

$S_S = 1/15$ for $T_z \geq 12$ [s]

with linear interpolation in between.

Based on the peak period the limiting criteria can be written:

$S_P = 1/15$ for $T_P \leq 8$ s

$S_P = 1/25$ for $T_P \geq 15$ s

which resembles the limit which may be used in towing tanks:

$$S_P = \frac{2\pi \cdot H_s}{g \cdot T_P^2} < 0{,}03$$

4. Wave Induced Response

The waves serve as the excitation for the wave induced response. The wave induced response is thereby the consequence of the waves acting on the hull surface. The wave induced response can be amongst others:

- all rigid motions including accelerations and velocities
- flexible motion and deformation of the structure like springing and whipping
- global hull girder loads
- local loads
- internal stress in the structure

Mathematically it may be expressed as:

$$y = a \cdot x$$

where:

x = input (excitation),

a = conversion factor

y = output (response).

The wave induced response is often referred to as only the response.

5. Linear Response

5.1 Introduction

Transfer functions (RAO and phase), short term and long term response are elements in most direct hydrodynamic calculations, and the concepts are briefly explained in the following.

5.2. Response Amplitude Operator (RAO)

The concept of transfer function, i.e. RAO is essential for sea-keeping assessments. An illustration of a poor and improved transfer function is given in Fig. 2.4. In case of linear theory the steady state solution x(t) of the equation of motions can be written as:

$$x(t) = A \cdot \mathrm{Re}\{\eta(\omega, \beta) \cdot \exp(i\omega_e t)\}, \qquad i = \sqrt{-1}$$

Where A is the incident single wave amplitude of a regular wave of frequency, ω, from wave direction, β, relative to the ship. The corresponding encounter frequency is denoted as ω_e. The real part of a complex number is denoted as Re{...}. The complex function η(ω, β) is the actual response-amplitude-operator RAO of response x. This function is provided by linear sea-keeping programs. Each component ηi of the vector η can always be expressed like:

$$\eta_i(\omega, \beta) = |\eta_i| \cdot \exp(i\theta_i)$$

where $|\eta_i|$ is the amplitude of the corresponding component of x(t) in case A = 1. The actual response component will have a peak when:

$$\omega_e t + \theta_I = 2\pi \cdot n$$

where n is an arbitrary integer. The real parameter θ_i is denoted the phase of the response component.

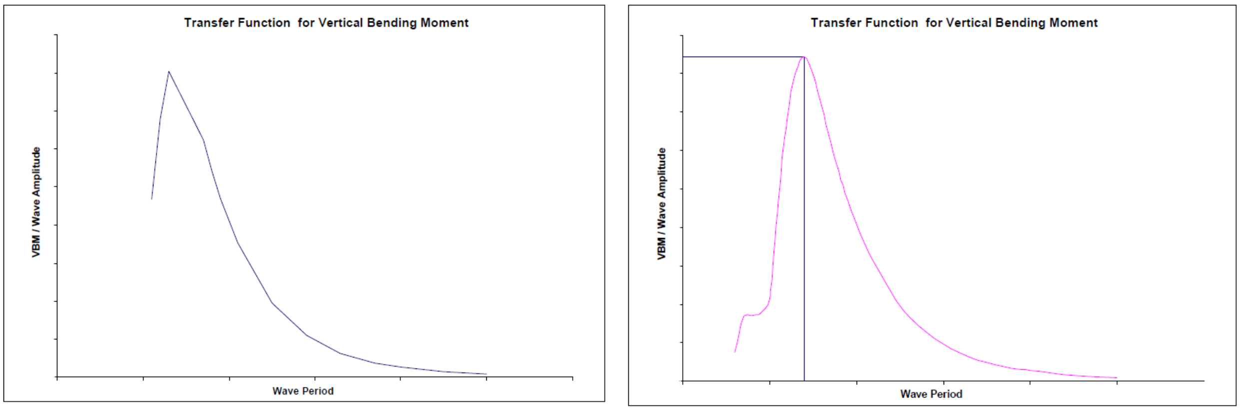

Fig. 2.4 Poor representation of a transfer function on the left, and on the right a transfer function where the peak and shorter wave periods are well represented

The phase explains the phase angle relative to the incident wave, e.g. phase equal to zero may be defined as cosine wave with crest amidships in the software. The phase, θ_i, lagging behind with e.g. positive π/2 implies that the peak response occurs 1/4th of the wave period later, i.e. after the wave crest has passed amidships and is located at the aft quarter length, if the wave length corresponds to the ship length in head sea. The phase tends to shift by about π, i.e. 180°, when the encounter frequency moves past the resonance frequency.

The concept of RAOs is applied for all linear responses including motions, accelerations, pressures, hull girder loads, disturbed wave elevation, etc. By including a linear structural model, RAOs can be established for stresses and strains at requested locations. However, stress formulations that are non-linear with respect to stresses, like Von-Mises stresses (equivalent stresses), cannot be represented by RAOs.

5.3 Short term response

Short term response implies that the transfer function has been combined with the wave spectrum and the wave spreading function. It defines the response in a sea state and the statistical properties can be estimated based on the response spectrum. The short term response gives properties as significant response, maximum value exceeded once during a sea state, mean response period, zero crossing period and kurtosis and skewness.

Wave spectra are explained in B.4 while wave energy spreading is explained in B.5. The response spectra can be interpreted as the energy distribution of the response with respect to frequency content similar to the wave spectra distribution. Derivation of response spectra is explained in B.2. The short term distribution of peaks may be represented by a distribution such as Rayleigh for Gaussian distributed responses (i.e. normal distributed). This is a good assumption in many linear cases. Another relevant distribution could be 2-parameter Weibull.

5.4 Long term Response

Long term response is estimated by combining the short term response from the individual sea states with the scatter diagram in B.3. Long term response is associated with a certain probability of being exceeded, e.g. 10^{-2} or 10^{-8}, or with a certain return period, e.g. 25 years. The return period is associated with a response which is exceeded once within the return period. An exceedance probability of 10^{-8} is the response, which is exceeded once amongst 10^{8} response cycles. A response with a return period of 25 years is close to equivalent with an exceedance probability of 10^{-8}.

The long term distribution is frequently represented by a 2-parameter Weibull distribution. The term straight line spectrum refers to the case where the inverse Weibull slope is 1.0.

The long term response value may be referred to as the most probable maximum. This concept is related to the extreme value distribution, which is a probability density function (pdf), and the peak value of this pdf is referred to as the most probable maximum. Even though there is a high likelihood of exceeding the most probable maximum, the extreme value distribution is narrow around the most probable maximum. The most probable maximum is also close to the expected maximum value in the extreme value distribution. The expected value is associated with 50% probability of being exceeded.

Section 3 Linear Wave Statistics

A. General

1. Objective

The objective of this section to define both short term and long term statistic variabilities, and the associated short term and long term distributions.

B. Short Term Statistics

1. The short-term is used to define one specific wave condition over a short duration (usually 3 hours) where the sea-state is considered as stationary.

2. Short-term ship responses is used to estimate the statistical response induced by a single stationary sea state defined by a wave spectrum. The ship speed and course are fixed. For linear response statistics, analytical results based on RAOs, given wave spectrum and duration can be established.

3. For non-linear responses the statistics become complicated especially for extreme value assessments. As an alternative, conservative scaling of linear results may be applied based on rule values.

4. Consistent with linear theory short term extreme values can be derived from the standard deviation σ of the response. The response spectrum can be interpreted as the energy distribution of the response with respect to wave (encounter) frequency ω_e and heading angle β. Given the RAO $\eta(\omega_e,\beta)$ for a given response, the response spectrum $R(\omega_e,\beta)$ is defined as:

$$R(\omega_e,\beta)=|\eta(\omega_e,\beta)|^2\cdot S(\omega_e,\beta)$$

where:

$S(\omega,\beta)$ = wave spectrum

$|\eta(\omega,\beta)|$ = amplitude of the RAO

ω_e = see Sec. 2, C 2.2

The moments of the response spectrum are defined as:

$$m_{\eta,n}=\int_0^{2\pi}\int_0^{\infty}\omega^n\cdot R(\omega_e,\beta)\,d\omega\,d\beta,\qquad n = 0, 1, 2, 3, \ldots$$

where:

n = 0, variance (standard deviation squared),

n = 1, the first moment,

n = 2, the moment of inertia of the spectra.

Short term statistics can be derived from the standard deviation σ of the response corresponding to the zero moment:

$$\sigma^2 = m_{\eta,0}$$

The significant response amplitude $\bar{\eta}_{1/3}$, is defined as the mean value of the highest one-third part of the amplitudes:

$$\bar{\eta}_{1/3} = 2 \cdot \sqrt{m_{\eta,0}}$$

The mean period T_1 and the average zero-crossing period T_z, [s], of the response are defined as:

$$T_1 = 2\pi \cdot \sqrt{\frac{m_{\eta,0}}{m_{\eta,1}}}$$

$$T_z = 2\pi \cdot \sqrt{\frac{m_{\eta,0}}{m_{\eta,2}}}$$

The expected extreme value $E[\eta_{max}]$ depends on the exposure time T_d in the actual sea state. For narrow banded linear processes a good approximation is given by:

$$E[\eta_{max}] = \sigma \cdot \sqrt{2 \cdot \ln\left(\frac{T_d}{T_z}\right)}$$

where T_z is the zero-crossing encounter period of the response. It should be noted that the probability of exceeding this value is 63%. However, the extreme value distribution is narrow for large durations and the response will usually not exceed this estimate significantly.

Another often applied metric is the extreme value, $\eta_{max,a}$, associated with a small prescribed exceedance, probability, α. A typical probability level is α = 0,05 which means that out of 20 cases, one is expected to exceed the limit. An approximate formula valid for narrow banded linear processes is:

$$\eta_{max,a} = \sigma \cdot \sqrt{2 \cdot \ln\left(\frac{T_d}{\alpha T_z}\right)}$$

5. The above formulas assume Rayleigh distributed response amplitudes. For broad-banded linear response the Rayleigh distributions should in principle be replaced by the Rice distribution. However, for practical computations the uncertainty related to the assumption of linear responses exceed the level of statistical effects from broad banded effects.

6. For long term statistics, the short term cumulative probability distribution, $F_{ST}(y|h, t, \beta, u)$ can be important. The probability of a response value being below y is conditional on the wave height, h, wave period, t, relative wave heading, β, and ship speed, u. In a short term case, these quantities can be considered as fixed, and at least the ship speed is often considered constant in long term statistics. The short term probability of exceeding the value y is then $Q_{ST}(y|h, t, \beta) = 1 - F_{ST}(y|h, t, \beta)$.

C. Long Term Statistics

1. The long-term statistic is used to define all the different wave conditions that can occur over a long period of time, usually several years, corresponding to the lifetime of the ships. As a consequence, the long term statistics combine results from various short term assessments as described in the previous section

2. The most common method for assessing long term statistics is to apply simple weighting of short term responses based on the probability of encountering various sea conditions. The weighting factor is defined by the probability of occurrence of each sea state as defined by the actual wave scatter diagram see Sec. 2, B.3.

3. Based on the short term cumulative probability distribution, $F_{ST}(y|h, t, \beta)$ for a constant speed case, the discretized long term distribution, $F_{LT}(y)$, can be given as:

$$F_{LT}(y) = \sum_{k=1}^{k_{max}} \sum_{j=1}^{j_{max}} \sum_{i=1}^{i_{max}} F_{ST}(y|h_k, t_j, \beta)\, f_{H_s,T_z}(h_k, t_j)\, f_\beta(\beta_i|h_k, t_j)\, \omega_{h_k,t_j,\beta}\, \Delta h \Delta t \Delta \beta$$

where

Δh, Δt, $\Delta\beta$ = grid size

$f_{Hs,Tz}$ = long term joint probability distribution taken from the scatter diagram

f_β = heading distribution

$\omega_{h,t,\beta}$ = the weight function

$$= \frac{T_{z,avg}}{T_z}$$

T_z = zero up-crossing period for the specific sea state [s]

$T_{z,avg}$ = long term average zero up-crossing period [s]

The long term value y_D for a given return period of T_{DF} years is given by:

$$F_{LT}(y_D) = 1 - \frac{1}{N_D} = 1 - \frac{T_{z,avg}}{T_{DF} \cdot 365{,}25 \cdot 24 \cdot 3600}$$

The probability that the long term value will be larger than y_D is given by:

$$Q_{LT}(y_D) = 1 - F_{LT}(y_D) = \frac{1}{N_D}$$

where N_D is the number of peaks during the T_{DF} years.

D. Probability of exceedance

1. The probability of exceedance, Q, of a response, y, depends on the number of cycles, n, exceeding a threshold, y', versus the total number of cycles, n_0, during a specified time period, e.g. design life. It can be written as:

$$Q(y > y') = \frac{n}{n_0}$$

Where,

$n_0 = \dfrac{T_{DF} \cdot 3600 \cdot 24 \cdot 365{,}25}{T_z}$

T_{DF} = design life [years]

T_z = long term zero up-crossing period [s]

2. The probability of exceedance associated with the extreme loading (ULS) is considered as 10^{-8}, while the probability of exceedance associated with fatigue loading is 10^{-2}. Both refer to the long term distribution during the design life and then the average T_z.

3. The probability of exceedance can also be associated with short term response in a sea state. Of interest is often the maximum response being exceeded only once during all the encountered response cycles during a sea state, which refer to a duration in the order of 3 hours. This maximum response may correspond to the maximum probable value from the extreme value distribution in case of Rayleigh distributed responses.

E. Return period and up-crossing rate

1. The return period T_R is always related to an event like exceeding a specific load level, L_L. The average time between each time the load exceed L_L is T_R. The up-crossing frequency or up-crossing rate, v, in 1/s, is defined as v = 1/T. For combined loads the terminology out-crossing rate is applied for v = 1/T.

2. A common misunderstanding exists that e.g. a 25-year event is likely to occur only once in a 25-year period. The correct interpretation is explained above. In general it should be noted that the probability of load level, L_L, to occur in any given year is P = $1/T_R$. Hence each (operational) year 4 of 100 sister ships are expected to exceed load level L_L if T_R = 25 years.

Section 4 Procedure for Wave Load Analysis

A. Introduction

Equivalent design waves (EDWs) are the basis for the wave loads in Rules for Bulk Carrier and Oil Tanker (Pt.1, Vol.XVII.B) Ch.4 for both FLS and ULS. The EDWs listed in E. are referred to as rule EDWs.

EDWs are a convenient alternative to statistical based loads, e.g. phase information is better maintained. Secondly, the long term value of the vertical bending moment is dominated by head seas, while the long term value of the side shell pressure is dominated by beam seas. These maximum values should not be used simultaneously, hence, in the statistical analysis correlation factors are needed. For EDWs in head seas, the vertical bending moment should be used with corresponding pressure, and in beam sea from port side, the port side pressure should be used with corresponding vertical bending. The phase information can then be included directly in a consistent way, which is important when many load components are included simultaneously. At the same time, the rule loads must assume a relevant distribution along the length, so that the number of EDW's can be reduced to a number that can be handled in a rule check. For this reason, the rule EDW are not fit for use on direct strength analysis. There are then in principle two EDW approaches; one for direct strength analysis and one for local strength assessment.

By applying the EDWs for different responses and headings in the structural analysis, the long term value of the stress at any position can be reproduced with sufficient accuracy. For each EDW there are two phases corresponding to a crest phase and a trough phase.

B. Method

1. Short term and long term prediction

The wave induced loads are to be calculated by numerical codes which are developed based on 3D linear potential theory considering perturbation induced by diffraction and radiation. The numerical codes are to be verified and validated by experimental data and the comparison report is to be submitted to the BKI for approval.

2. Numerical code

2.1 The envelope values of wave induced dynamic loads are calculated by short-term prediction using wave spectrum as specified in Sec. 3, B.4. and long term prediction for wave scatter diagram based on Sec. 3, B.3. For wave spreading as mentioned in Sec. 3, B.5 and Rayleigh distribution for wave height probability should be used.

2.2 The exceedance probability for strength assessment is 10^{-8} and recommended to use a speed of 5 knots. It is noted that it may be necessary to apply a higher speed when evaluating roll related responses for vessels with very low metacentric height and operating without reduced speed in stern quartering seas.

Furthermore, 75% of the design speed is recommended for evaluation of design wave loads for fatigue assessment.

2.3 The design wave loads at the probability level of 10^{-2} are selected for the fatigue assessment as the reference value to derive their long-term prediction distribution.

2.4 Heading angle occurrence should be taken with equal probability.

3. Equivalent Design Wave Method

Equivalent Design Wave (EDW) is the regular wave which can generate long-term prediction of load parameters. EDWs are determined for several dominant load parameters which govern ship structures or scantlings. For each EDW, two dynamic load cases (max. case, min. case) are to be considered. The strength assessment and fatigue assessment shall be carried out to satisfy the criteria for the dynamic load cases of all EDWs.

4. Analysis framework

The analysis framework of the direct method for obtaining wave induced dynamic loads is shown in Fig. 4.1. Detail information for each step are described in C. to H.

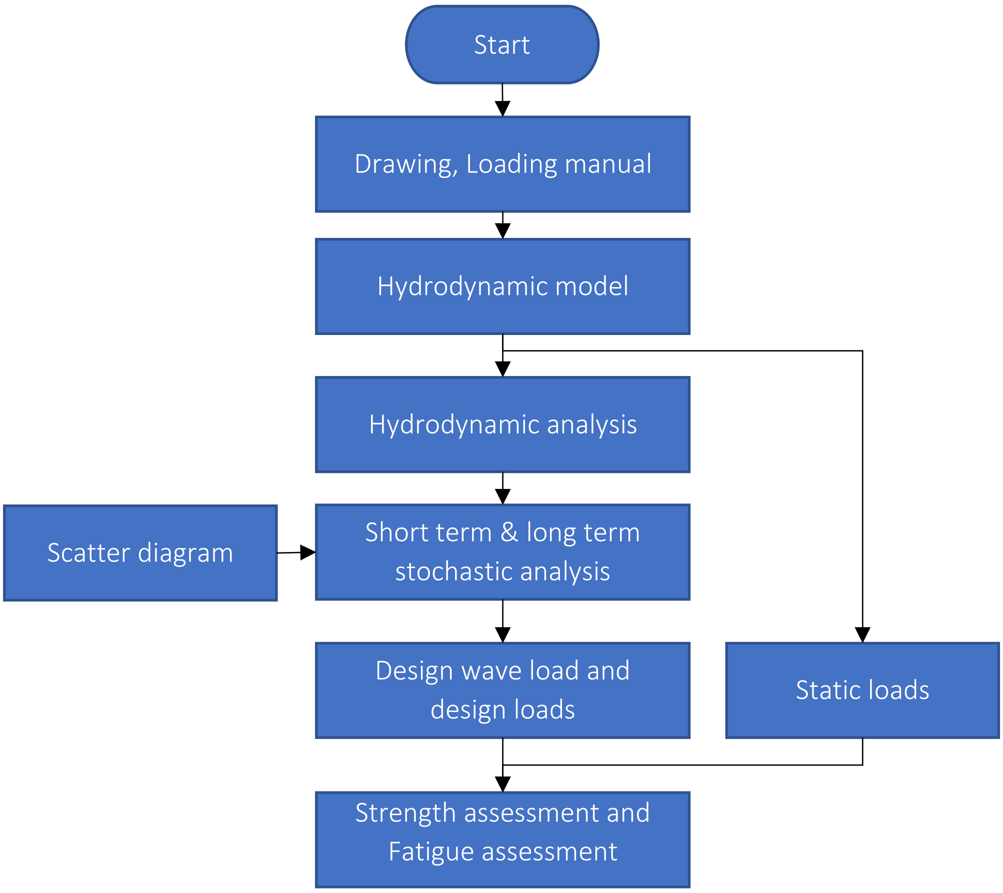

Fig. 4.1 Analysis framework for direct wave load analysis

C. Sea-keeping Analysis

1. Loading conditions

For oil tankers, following loading conditions are to be considered.

1) full loading condition
2) partial loading condition
3) ballast loading condition

For bulk carriers, following loading conditions are to be considered.

1) homogeneous full loading condition
2) alternate full loading condition
3) normal ballast loading condition
4) heavy ballast loading condition

2. Hydrodynamic model

The element size shall be sufficiently small to avoid numerical errors. At least 30-40 stations, including 15-20 panels at each station shall be applied. A good representation in areas with large transitions in shape (fore and aft part, bilge) shall be ensured using higher density of panels. Even areas with flat shape are to be divided into several panels to consider hydrodynamic pressure distribution and are not to be modelled by one large panel.

3. Mass model

3.1 Self weight

The weight of each structural member is the product of structure volume by material density, and the structure density may be increased properly to consider welding material and omitted minor structures. The additional weight shall be distributed properly over ship length to adjust the center of light ship weight.

3.2 Cargo weight

The cargo weights are to be considered to have the same longitudinal, vertical and transverse mass distribution in accordance with the trim/stability booklet.

4. Static balance

The hydrodynamic model and the weight model shall be in proper balance and give a good representation of the still water vertical bending moment distribution in the ship the trim/stability booklet. The displacement, longitudinal gravity center (LCG) and the still water vertical bending moment (SWBM) shall be checked to meet following tolerances compared with those from the trim/stability booklet.

– Displacement: 1%
– LCG: 0,1% of length
– SWBM: 5%

5. Calculation condition

5.1 Ship speed

The ship speed for strength assessment and for fatigue assessment are to be taken as B.2.2.

5.2 Wave heading angle

All heading angles from 0° to 360° are to be considered, with the heading angle interval less than 30˚

5.3 Wave frequency

Frequency ranges from 0,15 to 1,25 rad/sec are to be considered, with the frequency interval less than 0,05 rad/sec.

D. Stochastic Analysis

1. Short-term analysis

The short-term analysis is to be carried out based on the transfer functions obtained from the sea-keeping analysis and the wave spectrum which represents the total energy of irregular seaway. The JONSWAP spectrum is to be used for the North Atlantic, described in Section 2, B.4.

2. Long-term analysis

The long-term analysis is to be carried out based on the results of short-term analysis described in 1. and the wave data of the North Atlantic. The scatter diagram shown in Section 2, B.3 represents the wave data of the North Atlantic which covers the areas designated as blue area in Fig. 2.3.

E. Dynamic Load Cases

1. Determination of EDWs

The heading angle and the wave length of the design wave are chosen as the values where the relevant transfer function has its maximum and the design wave amplitude is chosen as the long-term value divided by the maximum value of the transfer function. If the wave steepness as defined in Section 2,B.2 is too high $\left(\frac{H}{\lambda} > \frac{1}{7}\right)$, it is necessary to choose a slightly longer wave length.

2. EDW used in the rules

EDW are denoted with a name where the two first letters represent the heading, while the third letter represents the response parameter. Number 1 or 2 are denoted the maximum or the minimum dominate load component for each EDW, while P or S are denoted that the weather side is on port side and on starboard side respectively, respectively. As the basis of design wave determination, EDW shall be chosen to assure that structural members, where extreme wave loads may act on or severe stresses may occur, are safe. Following EDWs at least shall be considered necessarily for strength assessment.

- HSM load cases:

  HSM-1 and HSM-2: Head sea EDWs that minimize and maximize the vertical wave bending moment amidships respectively.

- HSA load cases:

  HSA-1 and HSA-2: Head sea EDWs that maximize and minimize the head sea vertical acceleration at FP respectively

- FSM load cases:

  FSM-1 and FSM-2: Following sea EDWs that minimize and maximize the vertical wave bending moment amidships respectively.

– BSR load cases:

  BSR-1P and BSR-2P: Beam sea EDWs that minimize and maximize the roll motion downward and upward on the port side respectively with waves from the port side.

  BSR-1S and BSR-2S: Beam sea EDWs that maximize and minimize the roll motion downward and upward on the starboard side respectively with waves from the starboard side.

– BSP load cases:

  BSP-1P and BSP-2P: Beam sea EDWs that maximize and minimize the hydrodynamic pressure at the waterline amidships on the port side respectively.

  BSP-1S and BSP-2S: Beam sea EDWs that maximize and minimize the hydrodynamic pressure at the waterline amidships on the starboard side respectively.

– OST load cases:

  OST-1P and OST-2P: Oblique sea EDWs that minimize and maximize the torsional moment at 0,25 **L** from the AE with waves from the port side respectively.

  OST-1S and OST-2S: Oblique sea EDWs that maximize and minimize the torsional moment at 0,25 **L** from the AE with waves from the starboard side respectively.

– OSA load cases:

  OSA-1P and OSA-2P: Oblique sea EDWs that maximize and minimize the pitch acceleration with waves from the port side respectively.

  OSA-1S and OSA-2S: Oblique sea EDWs that maximize and minimize the pitch acceleration with waves from the starboard side respectively

The load components that are maximized for the strength assessment are exactly the same load components that are maximized for fatigue assessment. However, due to speed effects, the EDW that maximizes the vertical acceleration is the same EDW that maximizes the vertical wave bending moment. Therefore the load cases HSA and OSA are eliminated as they are redundant with load case HSM and OST.

3. Load combination factors

The load combination factor $C_{j,i}$ can be determined for each equivalent design wave using the response functions and long term predictions of the dominant load components and the subject load component by the following equation

$$C_{i,j} = \frac{H_i}{H_j} \frac{RAO_j(\lambda_i, x_i)}{RAO_{jmax}} \cdot \cos\{\varepsilon_j(\lambda_i, x_i) - \varepsilon_i(\lambda_i, x_i)\}$$

i	=	the i-th dominant load component of Sub 1, Ch 4, Sec 2 of the Rules
j	=	the j-th subject load component
H_i	=	the regular design wave height of the i-th dominant load component, in m.
H_J	=	the regular design wave height of the j-th subject load component, in m.
λ_i	=	the wave length of the dominant load component under the i-th equivalent design wave.
X_i	=	the wave encountering angle of the dominant load component under the i-th equivalent design wave.
$\varepsilon_j(\lambda_i, x_i)$	=	the phase angle of the dominant load component under the i-th equivalent design wave.

$\varepsilon_i(\lambda_i, x_i)$ = the phase angle of the dominant load component under the i-th equivalent design wave.

$RAO_j(\lambda_i, x_i)$ = the amplitude of the subject load component under the i-th equivalent design wave.

RAO_{jmax} = the maximum amplitude of the subject load component.

F. Hull Girder Loads

The dynamic hull girder load as stipulated in Rules for Bulk Carrier and Oil Tanker (Pt.1, Vol.XVII.B) Pt.1, Ch.4, Sec.4.3 shall be replaced with the following formula for determining direct EDW. If not define in below, any explanation of the symbols used in this formula shall be followed with Rules for Bulk Carrier and Oil Tanker (Pt.1, Vol.XVII).

1. Vertical wave bending moment

The vertical wave bending moments at any longitudinal position are to be taken as:

Hogging condition:

$$M_{wv-h} = 0{,}19 \cdot f_{M-direct} \cdot f_{nl-vh} \cdot f_m \cdot f_p \cdot C_w \cdot \mathbf{L}^2 \cdot \mathbf{B} \cdot C_B \qquad [\text{kNm}]$$

Sagging condition:

$$M_{wv-s} = -0{,}19 \cdot f_{M-direct} \cdot f_{nl-vs} \cdot f_m \cdot f_p \cdot C_w \cdot \mathbf{L}^2 \cdot \mathbf{B} \cdot C_B \qquad [\text{kNm}]$$

where,

$$f_{M\text{-direct}} = \frac{M_{wv-direct}}{0{,}19 \cdot f_m \cdot f_p \cdot C_w \cdot \mathbf{L}^2 \cdot \mathbf{B} \cdot C_B} \quad \text{but not less than 1,0.}$$

2. Vertical wave shear force

The vertical wave shear forces at any longitudinal position are to be taken as:

$$Q_{wv-pos} = 0{,}52 \cdot f_{Q-direct} \cdot f_{q-pos} \cdot f_p \cdot C_w \cdot \mathbf{L} \cdot \mathbf{B} \cdot C_B \qquad [\text{kN}]$$

$$Q_{wv-pos} = -0{,}52 \cdot f_{Q-direct} \cdot f_{q-pos} \cdot f_p \cdot C_w \cdot \mathbf{L} \cdot \mathbf{B} \cdot C_B \qquad [\text{kN}]$$

where,

$$f_{Q\text{-direct}} = \frac{Q_{wv-direct}}{0{,}52 \cdot f_p \cdot C_w \cdot \mathbf{L} \cdot \mathbf{B} \cdot C_B} \quad \text{but not less than 1,0}$$

3. Horizontal wave bending moment

The horizontal wave bending moment at any longitudinal position is to be taken as:

$$M_{wh} = f_{MH-direct} \cdot f_{nlh} \cdot f_p \cdot \left(0{,}31 + \frac{\mathbf{L}}{2800}\right) \cdot f_m \cdot C_w \cdot L^2 \cdot T_{LC} \cdot C_B \qquad [\text{kNm}]$$

where,

$$f_{MH\text{-}direct} = \frac{M_{wh-direct}}{f_p\left(0{,}31+\frac{L}{2800}\right)\cdot f_m\cdot C_w\cdot L^2\cdot T_{LC}\cdot C_B} \quad \text{but not less than 1,0}$$

4. Wave torsional moment

The wave torsional moment at any longitudinal position with respect to the ship baseline is to be taken as:

$$M_{wt} = f_{MT-direct}\cdot f_p\cdot\left(M_{wt1}+M_{wt2}\right) \quad [kNm]$$

where,

$$f_{MT\text{-}direct} = \frac{M_{wt-direct}}{f_p\cdot\left(M_{wt1}+M_{wt2}\right)} \quad \text{but not less than 1,0}$$

G. Ship Motions and Accelerations

The acceleration for dynamic load cases as stipulated in Rules for Bulk Carrier and Oil Tanker (Pt.1, Vol.XVII.B) Pt.1, Ch.4, Sec.3.3 shall be replaced with the following formula for determining direct EDW. If not define in below, any explanation of the symbols used in this formula shall be followed with Rules for Bulk Carrier and Oil Tanker (Pt.1, Vol.XVII).

1. Longitudinal acceleration

The longitudinal acceleration at any position for each dynamic load case is to be taken as:

$$a_X = -C_{XG}\cdot g\cdot\sin\left(f_{\varphi-direct}\,\varphi\right)+C_{XS}\cdot f_{surge-direct}\cdot a_{surge}+C_{XP}\cdot f_{pitch-direct}\cdot a_{pitch}\cdot\left(Z-Z_{CG}\right) \quad [m/s^2]$$

where,

$$f_{\varphi\text{-}direct} = \frac{\varphi_{direct}}{\varphi} \quad \text{but not less than 1,0}$$

$$f_{surge\text{-}direct} = \frac{a_{surge-direct}}{a_{surge}} \quad \text{but not less than 1,0}$$

$$f_{pitch\text{-}direct} = \frac{a_{pitch-direct}}{a_{pitch}} \quad \text{but not less than 1,0}$$

Z_{CG} = vertical center of gravity of ship

2. Transverse acceleration

The transverse acceleration at any position for each dynamic load case is to be taken as:

$$a_Y = C_{YG}\cdot g\cdot\sin\left(f_{\theta-direct}\,\theta\right) + C_{YS}\cdot f_{sway-direct}\cdot a_{sway} - C_{YR}\cdot f_{roll-direct}\cdot a_{roll}\cdot\left(Z-Z_{CG}\right) \quad [m/s^2]$$

where,

$$f_{\theta\text{-}direct} = \frac{\theta_{direct}}{\theta} \quad \text{but not less than 1,0}$$

$f_{sway\text{-}direct}$ = $\frac{a_{sway-direct}}{a_{sway}}$ but not less than 1,0

$f_{roll\text{-}direct}$ = $\frac{a_{roll-direct}}{a_{roll}}$ but not less than 1,0

Z_{CG} = as specified in 1.

3. Vertical acceleration

The vertical acceleration at any position for each dynamic load case is to be taken as:

$$a_Z = C_{ZH} \cdot a_{heave} + C_{ZR} \cdot f_{roll-direct} \cdot a_{roll} \cdot y - C_{ZP} \cdot f_{pitch-direct} \cdot a_{pitch} \cdot (X - X_{CG}) \quad [m/s^2]$$

where,

$f_{roll-direct}$ = as specified in 2.

$f_{pitch-direct}$ = as specified in 1.

X_{CG} = longitudinal center of gravity of ship

H. Dynamic Pressures

The external dynamic pressure according to Rules for Bulk Carrier and Oil Tanker (Pt.1, Vol.XVII.B) Pt.1, Ch.4, Sec.5.1 shall be corrected with the following formula for determining direct EDW. The external hydrodynamic pressures, at any point are to be taken as:

$$P_{W,WL-linear} = P_{W,WL} \quad (k_a = 1,0 \; ; \; k_p = 1,0 \; ; \; k_{nl} = 1,0) \quad [kN/m^2]$$

$$P_{LC} = f_{P-direct} \cdot P_{LC-rule} \quad [kN/m^2]$$

where,

$P_{LC-rule}$ = external pressure of Rules for Bulk Carrier and Oil Tanker (Pt.1, Vol.XVII.B) Pt.1, Ch.4, Sec. 5, P_{HS}, P_{FS}, P_{BSR}, P_{BSP}, P_{OST}, P_{OSA}

$f_{p\text{-}direct}$ = $\frac{P_{W,WL-direct}}{P_{W,WL-linear}}$ but not less than 1,0