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GUIDELINES FOR DIRECT CALCULATION ASSESSMENT OF HULL STRUCTURE INCLUDING SPRINGING AND WHIPPING

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Contents

Chapter 1 General

1.1 Application

1.1.1 The Guidelines specify assessment methods for hull structure fatigue strength and hull girder ultimate strength taking account of loads induced by springing and whipping. The Guidelines are applicable to ships that are required to be subject to springing and whipping assessment by CCS rules or guidelines, and ships applying for the notations specified in 1.1.3 of this Chapter on a voluntary basis, or ships for which CCS regards springing and whipping effects need to be taken into account.

1.1.2 Ships meeting the following conditions may be required to carry out analysis of springing and whipping effects:

a) $L > 300$ m;

where: L —— length of ship, in m, see the relevant definition in Section 1, Chapter 1, PART TWO of CCS Rules for Classification of Sea-going Steel Ships.

b) $f_{ec} > f_{2n}$;

where: f_{ec} —— critical wave encounter frequency to consider springing and whipping effects, in Hz, to be calculated as follows:

$$f_{ec} = 0.318 + 0.017V$$

where: V —— maximum service speed, in m/s, see the relevant definition in Section 1, Chapter 1, PART TWO of CCS Rules for Classification of Sea-going Steel Ships;

f_{2n} —— frequency of 2-node vertical vibration mode of hull girder, in Hz, where exact data is not available, it may be obtained by the following formula:

$$f_{2n} = 5.117 \times 10^4 \sqrt{\frac{I_{ov}}{\Delta_v L_{pp}^3}}$$

where: I_{ov} —— moment of inertia of amidship section, in m^4;

L_{pp} —— length between perpendiculars, in m;

Δ_v —— virtual displacement including added mass of water, in t, to be calculated as follows:

$$\Delta_v = \left(1.2 + \frac{B}{3d}\right)\Delta$$

where: B —— moulded breadth, in m;

d —— mean draft of vessel in the loading condition for calculation, in m;

Δ —— vessel displacement, in t.

c) $\alpha > 45°$.

where: α —— flare angle, see the relevant definition in Section 8, Chapter 7, PART TWO of CCS Rules for Classification of Sea-going Steel Ships, in (°), to be taken as half the vertical distance between the summer loadline draft and the uppermost deck 0.1L after the forward perpendicular.

For ships meeting conditions a) and b), hull structure fatigue strength assessment taking into account linear springing may be carried out according to 3.3 of the Guidelines.

For ships meeting conditions a), b) and c), hull structure fatigue strength assessment taking into account springing and whipping may be carried out according to 4.4 of the Guidelines.

For ships meeting conditions a) and c), hull girder ultimate strength assessment taking into account whipping may be carried out according to 5.3 of the Guidelines.

For other ships, the Guidelines may also be referred to for springing and whipping strength assessment of their hull structures.

1.1.3 Class notations

(1) For ships the fatigue strength of which is assessed according to 3.3 of the Guidelines, the class notation SAF may be assigned.

(2) For ships the fatigue strength of which is assessed according to 4.4 of the Guidelines, the class notation SWAF may be assigned.

(3) For ships the ultimate strength of which is assessed according to 5.3 of the Guidelines, the class notation WAU may be assigned.

1.1.4 The Guidelines are to be applied in conjunction with CCS Guidelines for Fatigue Strength of Ship Structure, Rules for Classification of Sea-going Steel Ships or Rules for Construction of Sea-going Ships engaged on Domestic Voyages for fatigue strength and ultimate strength assessment of hull structure.

1.2 Springing and whipping phenomenon

1.2.1 When the rigidity of the hull girder is relatively low and the ship speed is relatively high, the hull structure will be subject to continuous high-frequency vibration without obvious attenuation under wave excitation, resulting in the so-called "springing" phenomenon, which is a resonance phenomenon between the hull structure and the wave action. Springing usually occurs when the first-order vertical total vibration frequency of hull is equal to or close to the encountered wave frequencies, i.e. linear springing; when the first-order vertical total vibration frequency of hull girder is equal to or close to integer multiples of the encountered wave frequencies or the sum frequency of dichroic (or polychromatic) waves, springing will also occur to the hull, i.e. non-linear springing. Springing is characterized by high frequency, and usually occurs in low and medium sea states, affecting mainly the fatigue strength of the structure. Springing can be calculated and forecast by means of linear frequency domain hydroelasticity method with spectrum analysis or non-linear time domain hydroelasticity method with statistical analysis.

1.2.2 When ships sail in medium or severe sea states at a higher speed, substantial relative movement between the ship and the wave will make the hull subject to strong wave impact, and the hull structure, due to the instantaneous high-frequency vibration with rapid attenuation caused by slamming load, will be subject to the so-called "whipping" phenomenon; it is a forced vibration phenomenon due to wave slamming on the hull. Whipping not only brings the total stress level of the hull structure to a higher level, but also affects the ultimate strength of the hull girder, as its high-frequency characteristic will also affect the fatigue strength of the structure. Due to the strong non-linear characteristics of whipping, the non-linear time domain hydroelasticity method with statistical analysis is to be used for calculation and forecast.

1.2.3 For fatigue strength assessment of hull structure taking into account linear springing , the method of linear frequency domain hydroelasticity and spectrum analysis is to be used to calculate and forecast. For fatigue strength assessment of hull structure taking into account whipping and springing, the non-linear time domain hydroelasticity and statistical analysis method is to be used to calculate and forecast, where the whipping response and the springing response are to be coupled together.

1.3 Basic assumptions

1.3.1 Only the effects of springing and whipping on vertical wave bending moment of hull girder are considered.。

1.3.2 The hydroelastic response effect is to be considered in the direct calculation of loads.

1.3.3 The fatigue strength assessment methods of hull structure with regard to springing and whipping are to be consistent with those specified in CCS Guidelines for Fatigue Strength of Ship Structure.

1.3.4 The calculation methods for permissible still water bending moment, wave bending moment as well as ultimate bearing capacity of hull girder used in the ultimate strength assessment of hull girder with regard to whipping are to be consistent with those specified in CCS rules for relevant ship types.

1.3.5 For vertical vibration of hull girder, at least the first three order vertical modes are to be taken.

1.4 Springing and whipping assessment procedures

1.4.1 Fatigue strength assessment procedure of hull structure taking into account linear springing

Vertical wave bending moment of hull girder is calculated based on liner hydroelasticity theory and spectrum analysis method. The resulting wave bending moment consists of low frequency and high frequency components, where the low-frequency component is the vertical wave bending moment without springing (i.e., wave frequency component), the high frequency component is the vertical wave bending moment induced by springing, and the total bending moment is the vertical wave bending moment including the low frequency component and the high frequency component. The wave frequency component stress response of the vertical wave bending moment and the total bending moment stress response are applied to the fatigue damage calculation respectively, and fatigue strength assessment of hull structure taking into account linear springing is to be carried out in accordance with the procedure specified in Figure 1.4.1.

1.4.2 Fatigue strength assessment procedure of hull structure taking into account whipping and springing

Time history of vertical wave bending moment of hull girder is calculated based on non-liner wave load time domain approach, including bending moment induced by whipping and springing. The resulting wave bending moment consists of low frequency and high frequency components, where the low-frequency component is the vertical wave bending moment without whipping and springing (i.e., wave frequency component), the high frequency component is the vertical wave bending moment induced by whipping and springing, and the total bending moment is the vertical wave bending moment including the low frequency component and the high frequency component. The wave frequency component stress response of the vertical wave bending moment and the total bending moment stress response are applied to the fatigue damage calculation respectively, and fatigue strength assessment of hull structure taking into account whipping and springing is to be carried out in accordance with the procedure specified in Figure 1.4.2.

1.4.3 Ultimate strength assessment procedure of hull girder taking into account whipping

Time history of vertical wave bending moment of hull girder is calculated based on non-liner wave load time domain approach, including bending moment of flexible body induced by whipping and bending moment of rigid body induced by non-linear wave. Weibull fitting analysis is carried out on the peak response of bending moment in different sea states, and the extreme values of whipping bending moment of flexible body and nonlinear bending moment of rigid body are determined according to the long-term extreme value forecast theory by considering the cumulative probability such as service speed, wave direction and sea state. Ultimate strength assessment of hull structure taking into account whipping is to be carried out in accordance with the procedure specified in Figure 1.4.3 according to the extreme values of the two kinds of bending moment considering the increase in wave bending moment of hull girder caused by whipping.

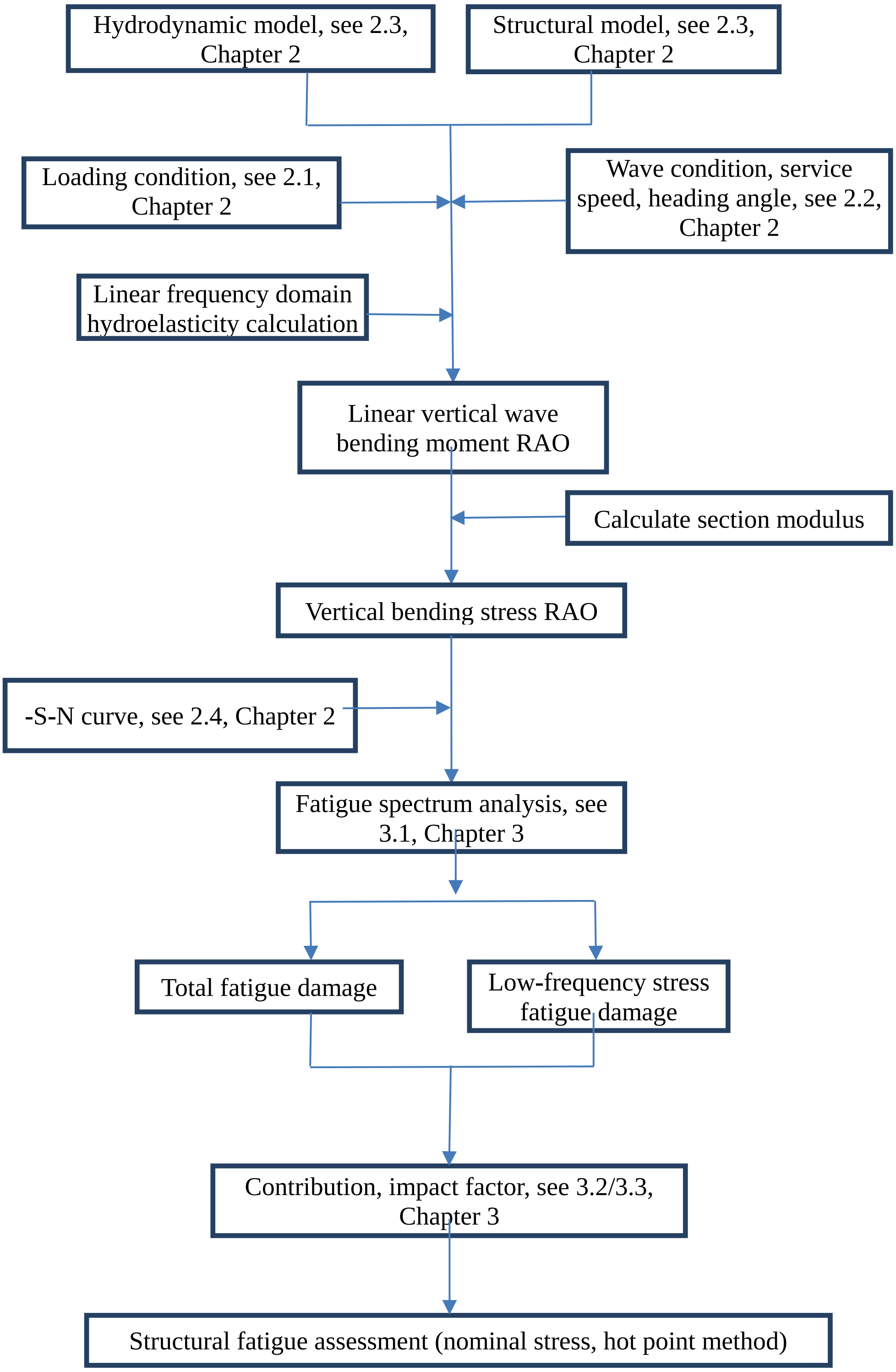

Figure 1.4.1 Fatigue strength assessment procedure of hull structure taking into account linear springing

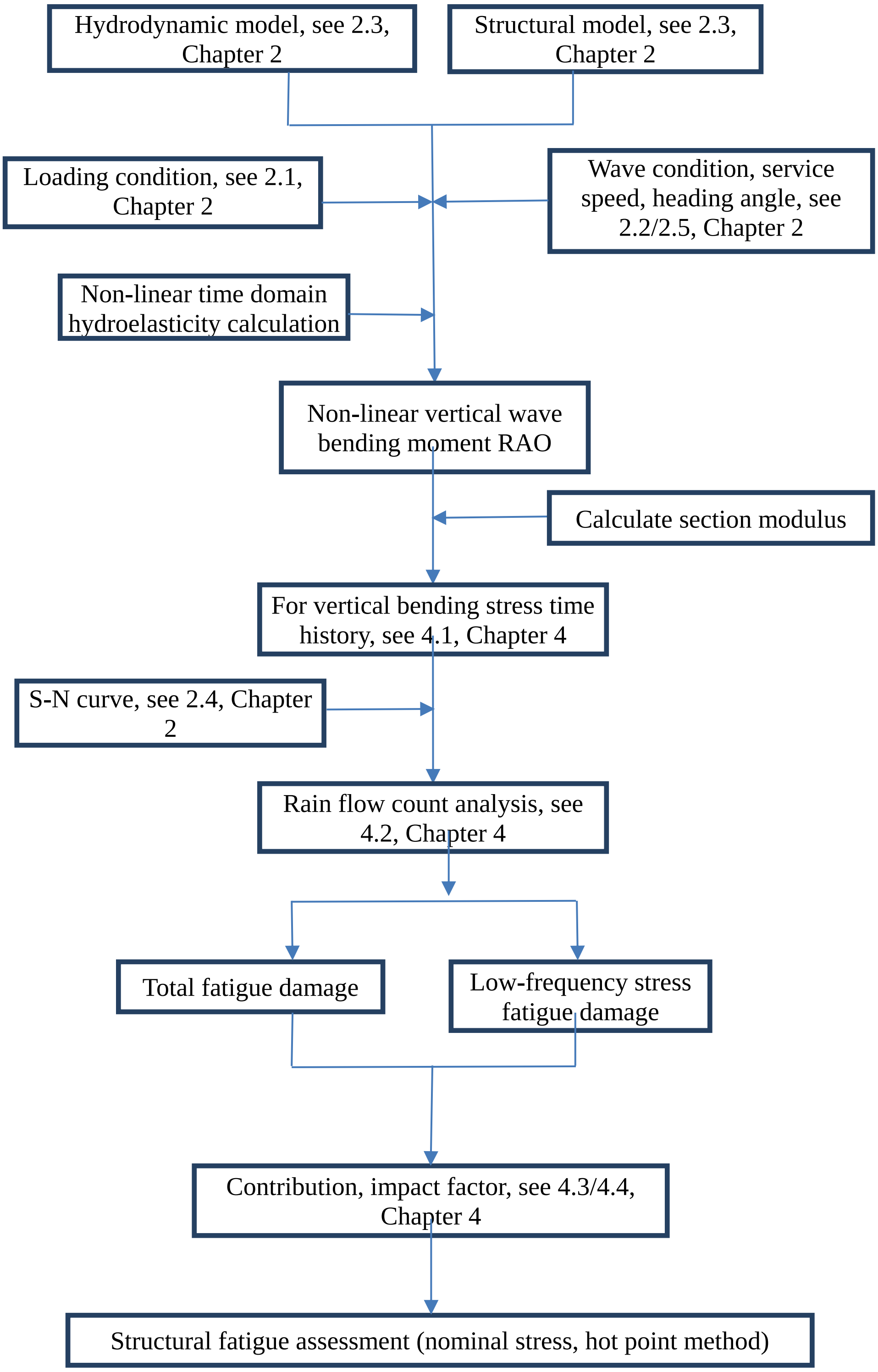

Figure 1.4.2 Fatigue strength assessment procedure of hull structure taking into account whipping and springing

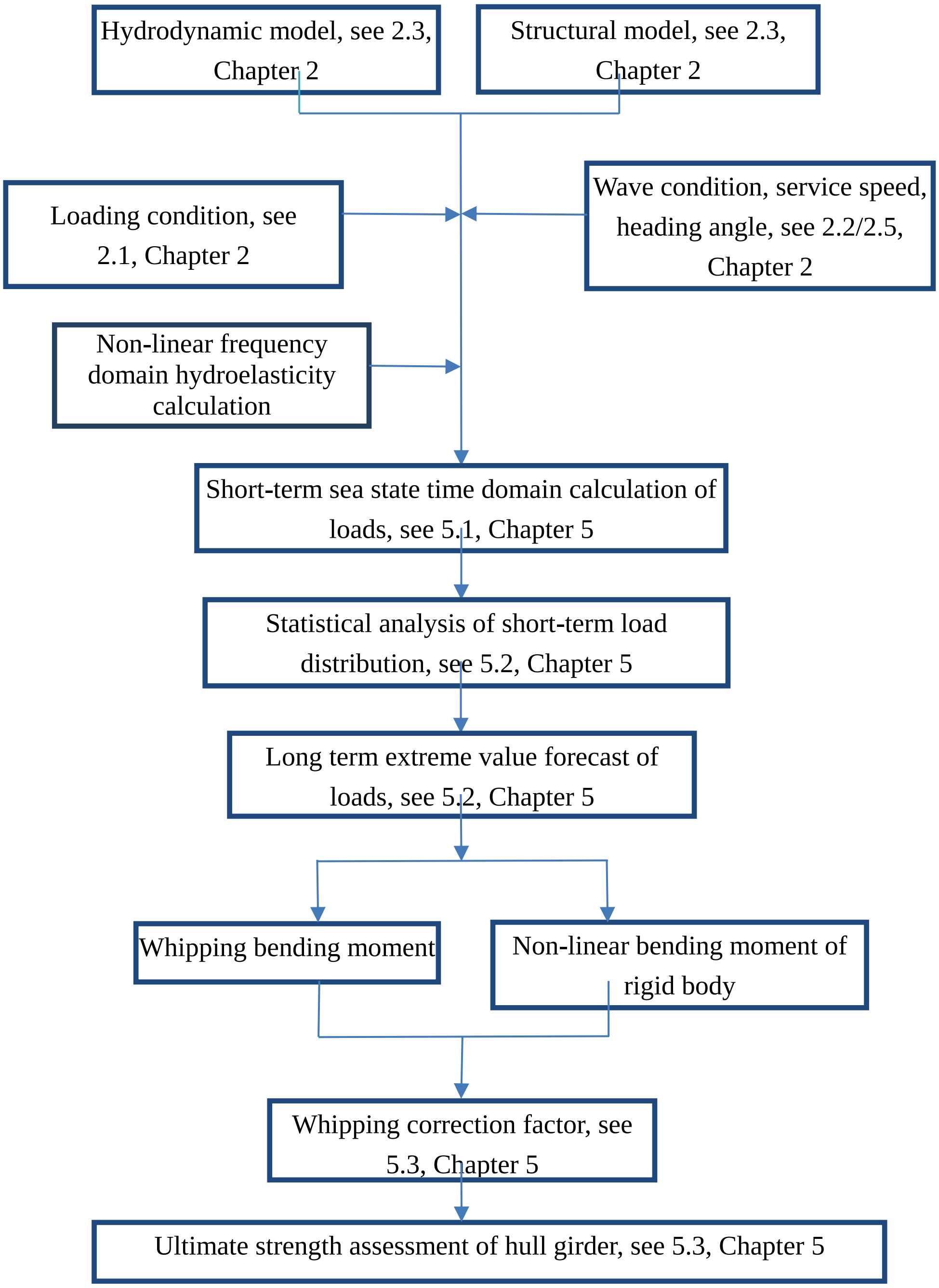

Figure 1.4.3 Ultimate strength assessment procedure of hull girder taking into account whipping

1.5 Symbols

H_S —— significant wave height, in m;

T_Z —— average zero up-crossing wave period, in s;

ω —— circular frequency of wave, in $\mathrm{rad/s}$;

θ —— wave heading angle, following sea is 0°, and head sea is 180°;

g —— gravity acceleration, to be taken as 9.81 $\mathrm{m/s^2}$;

m —— inverse slope of the S-N curve;

Δm —— slope change of the upper-lower segment of the S-N curve;

$\Gamma(x, v)$ —— incomplete GAMMA function;

$\Gamma(x)$ —— complete GAMMA function;

T —— calculated fatigue life, in s, $T = 3.1557 \times 10^7 f_t T_D$;

T_D —— design fatigue life, in year;

f_t —— service coefficient, to be same as that specified in CCS Guidelines for Fatigue Strength of Ship Structure;

n_l, n_s, n_h —— sum of loading conditions, sea states and wave headings respectively;

p_n,p_j,p_i —— occurrence probability of the n-th loading condition, the j-th sea state and the i-th wave heading respectively;

$\Delta\sigma_{HG,WV}$ —— stress range due to vertical wave bending moment of hull girder, in $\mathrm{N/mm^2}$, to be calculated as follows:

$$\Delta\sigma_{HG,WV} = \frac{M_{WV,H} - M_{WV,S}}{W_v}$$

where: $M_{WV,H}$—— wave bending moment for hogging not considering the impacts of springing and whipping, in kNm, to be calculated as per the relevant provisions in Section 3, Chapter 2 of CCS Guidelines for Fatigue Strength of Ship Structure;

$M_{WV,S}$—— wave bending moment for sagging not considering the impacts of springing and whipping, in kNm, to be calculated as per the relevant provisions in Section 3, Chapter 2 of CCS Guidelines for Fatigue Strength of Ship Structure;

W_v —— vertical section modulus of the calculation point, in $\mathrm{cm^3}$;

ξ —— long term distribution parameter of stress ranges following the Weibull distribution, to be taken as per the relevant provisions in Section 5, Chapter 3 of CCS Guidelines for Fatigue Strength of Ship Structure;

N_R —— number of cycles corresponding to the given probability of exceedance, to be taken as per the relevant provisions in Section 5, Chapter 3 of CCS Guidelines for Fatigue Strength of Ship Structure.

Chapter 2 Calculation Conditions

2.1 Loading conditions

2.1.1 Loading conditions for assessing the fatigue strength of hull structure taking into account springing and whipping are generally to be consistent with those specified in Section 7, Chapter 1 of CCS Guidelines for Fatigue Strength of Ship Structure. Special circumstances may be considered separately.

2.1.2 Loading conditions for assessing the ultimate strength of hull girder taking into account whipping are to be those that have the maximum still water hogging bending moment and still water sagging bending moment respectively selected from the Loading Manual. For container ships, the condition for the maximum still water hogging bending moment is to be selected from the navigation condition fully loaded at the maximum draught.

2.2 Wave environment

2.2.1 Wave scatter diagram

For ships in unrestricted service, the wave scatter diagram for North Atlantic from IACS Rec.34 is generally to be used. Special circumstances may be considered separately.

2.2.2 Wave spectrum

The power spectral density function of wave $S(\omega)$ is generally adopted as the two-parameter P-M spectrum:

$$S(\omega) = \frac{124H_S^2}{T_Z^4}\omega^{-5}exp\left(-\frac{496}{T_Z^4}\omega^{-4}\right)$$

The actual response frequency is the encounter frequency ω_e, which is to be calculated as follows:

$$\omega_e = \omega\left(1 - \frac{\omega V_c}{\mathrm{g}}cos\theta\right)$$

where: V_c —— service speed for calculation, in m/s, see 2.2.3 of this Chapter.

2.2.3 Service speed

Except for the specified service speed, four service speeds for calculation V_c are generally used for springing and whipping calculation as follows, and they are not to be less than 5kn:

$$V_c = \begin{cases} 100\%V & \text{for } 0 < H_S \le 6.0\text{m} \\ 75\%V & \text{for } 6.0\text{m} < H_S \le 9.0\text{m} \\ 50\%V & \text{for } 9.0\text{m} < H_S \le 12.0\text{m} \\ 25\%V & \text{for } 12.0\text{m} < H_S \end{cases}$$

2.2.4 Wave heading angle

Except for the specified wave heading angles and their corresponding probability of occurrence in ship design, the wave heading angle is generally to be taken between 0° and 360° in increments of not more than 30°. The probability of occurrence for each wave heading angle is equal.

2.3 Calculation requirements

2.3.1 Hydrodynamic calculation

(1) For each loading condition, the computed values of displacement, trim, and longitudinal center of buoyancy and still water bending moment are to be checked against the values of the trim and stability booklet. The differences are to be within the following tolerances:

Displacement: $\pm 1\%$;

Trim angle: $\pm 0.1(°)$;

Longitudinal center of buoyancy: $\pm 0.2\% L$;

Still water bending moment: $\pm 10\%$.

Meanwhile, draft at aft perpendicular and forward perpendicular and transverse and longitudinal metacentric height are also to be checked.

(2) The free surface GM correction is to be considered for partially filled tanks. For a tank with filling level above 98% or below 2% of the tank height, the free surface GM correction may be ignored.

(3) Experimental data or empirical methods can be used for the determination of the viscous roll damping. If this information is not available, 5% of critical damping may be used for overall viscous roll damping.

(4) In the calculation of linear springing Response Amplitude Operators (RAO), the encounter frequency range of the ship is at least to cover the 2-node vertical vibration frequency of hull girder. The recommended wave frequency input range is $[0,3.0]\mathrm{rad/s}$, and the frequency step is not to be more than $0.3\sqrt{\mathrm{g}/L}$.

(5) In the 3D hydrodynamic model calculation, the mesh size is to be chosen considering the compatibility of the minimum encountered wave length, service speed and irregular wave frequency so as to obtain stable and converged numerical solution. The mesh number of the hydrodynamic model wet surface is not to be less than 5000.

2.3.2 Vibration mode calculation

The hull girder can be simplified into a beam model which has variable cross-sections (21 or above) and is free at both ends. Dry mode of hull girder vibration may be calculated according to transfer matrix method or FE method, and mass per unit length, vertical vibration moment of inertia, shear area as well as bending moment of inertia of each section are to be considered.

2.3.3 Stress response of hull structure may be calculated using beam model or FE method.

2.3.4 Experimental data or empirical methods can be used for the determination of the structural damping. If this information is not available, 1% and 3% of the critical damping may be used for ballast and full load conditions, respectively.

2.4 S-N curve for fatigue calculation

2.4.1 The S-N curve form given in 2.4.2 of this Chapter is generally to be used. Where other S-N curve forms are used, the fatigue damage calculation formula in 3.1.2, Chapter 3 is to be specially considered.

2.4.2 The S-N curve is generally represented as follows:

$$\begin{cases} NS^m = C & \text{for } S > S_Q \\ NS^{m+\Delta m} = K & \text{for } S \leq S_Q \end{cases}$$

where: S —— stress range, in $\mathrm{N/mm^2}$;

N —— number of fatigue failure cycles corresponding to S;

$C,\ K$ —— constant of S-N curve;

S_Q —— stress range value of S-N curve between the intersections of two lines, in $\mathrm{N/mm^2}$.

2.5 Simplification of whipping calculation condition

2.5.1 For ships in unrestricted service, simplified conditions given in 2.5.2 and 2.5.3 of this Chapter may be used to carry out non-linear time domain whipping calculation assessment.

2.5.2 Fatigue loads calculation condition for whipping

In order to calculate the fatigue loads for whipping, the calculation condition may be selected according to the following scheme:

1) heading angles: in the range between head sea and oblique wave at 60° in increments of not more than 30°, and the probability of occurrence is determined based on equal probability of all wave headings;

2) sea states: 98 sea states with the significant wave height below 12 m and the probability of

occurrence above 0.0001 in the wave scatter diagram of IACS Rec.34.

2.5.3 Ultimate loads calculation condition for whipping

In order to calculate the ultimate loads for whipping, the calculation condition may be selected according to the following steps:

(1) calculation of all wave headings linear Response Amplitude Operator (RAO) is carried out on vertical wave bending moment of the amidship section;

(2) short-term forecast of all wave headings and all sea states is carried out for the vertical wave bending moment according to the wave scatter diagram of IACS Rec.34;

(3) long-term extreme value analysis is carried out according to linear short-term forecast result, and the calculation condition is selected according to the following scheme:

1) heading angles: in the range between head sea and oblique wave at 30° in increments of not more than 30°, and the probability of occurrence is determined based on equal probability of all wave headings;

2) sea states: 50 sea states with the significant wave height above 12 m and the maximum contribution ratio to the long-term extreme value of the vertical wave bending moment.

The long-term extreme value of the vertical wave bending moment in the simplified condition calculation is not to be lower than 98.5% of the linear long-term extreme value of all wave headings and all sea states. Where this requirement cannot be met, more sea states are to be calculated according to the contribution ratio.

Chapter 3 Fatigue Strength Assessment of Hull Structure Subject to Linear Springing

3.1 Calculation of fatigue damage

3.1.1 Short-term distribution of stress range

(1) Stress response due to wave frequency component of vertical bending moment

The response spectrum of stress, $S_\sigma(\omega)$, is to be calculated as follows:

$$S_\sigma(\omega) = |H_\sigma(\omega)|^2 S(\omega)$$

where: $S(\omega)$ —— power spectral density function of wave, see 2.2.2 of Chapter 2;

$H_\sigma(\omega)$ —— transfer function for stress response, in $(\mathrm{N}/mm^2)/\mathrm{m}$, to be calculated as follows:

$$H_\sigma(\omega) = \frac{H(\omega)}{W_v} 10^{-3}$$

where: $H(\omega)$ —— transfer function of vertical bending moment at the considered hull section, in $(\mathrm{kN} \cdot \mathrm{m})/\mathrm{m}$;

W_v —— vertical section modulus at calculation point, in m^3.

The 0-th order moment m_0, 2nd order moment m_2 and 4-th order moment m_4 of power spectral density are to be calculated as follows:

$$m_n = \int_0^\infty \omega^n S_\sigma(\omega) d\omega \quad (n = 0,2,4)$$

The standard deviation, σ_x, in the process of alternating stress is the function of 0-th order moment of the stress response spectrum:

$$\sigma_x = \sqrt{m_0}$$

The average zero up-crossing frequency of stress, f_0, induced by wave loads is to be calculated as follows:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{m_2}{m_0}}$$

The bandwidth correction factor, $\lambda(m, \varepsilon)$, is to be calculated as follows:

$$\lambda(m, \varepsilon) = a(m) + [1 - a(m)](1 - \varepsilon)^{b(m)}$$

where: $a(m) = 0.926 - 0.033m$;

$b(m) = 1.587m - 2.323$;

$\varepsilon = \sqrt{1 - \frac{m_2^2}{m_0 m_4}}$.

(2) Stress response to total bending moment of hull hydroelasticity

The statistical characteristics of the narrow-band stress response (e.g. standard deviation of response) to wave frequency component (rigid body response) and springing component (hydroelastic high-frequency response) are to be calculated respectively as follows:

$$\text{Wave frequency component: } m_{wave-n} = \int_0^{\omega_1} \omega^n S_\sigma(\omega) d\omega$$

$$\text{Springing component: } m_{springing-n} = \int_{\omega_1}^{\infty} \omega^n S_\sigma(\omega) d\omega$$

where: $S_\sigma(\omega)$ —— Spectral density function of stress response, see 3.1.1(1) in this Chapter;

ω_1 —— Critical frequency value between wave frequency component and springing component, as shown in Figure 3.1.1.

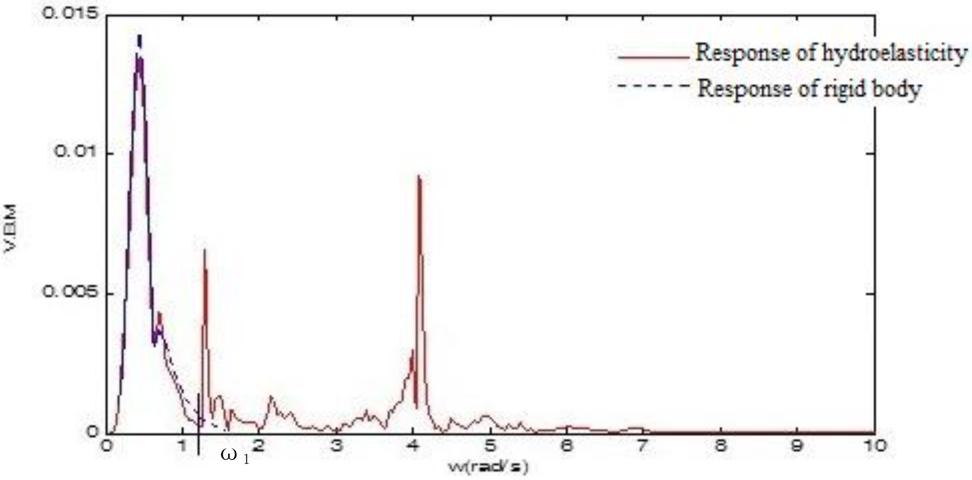

Figure 3.1.1 Typical frequency domain response to vertical wave bending moment of flexible ship hull

The zero up-crossing frequency of wave frequency component f_{wave} and zero up-crossing frequency of springing component $f_{springing}$ are to be calculated respectively as follows:

$$f_{wave} = \frac{1}{2\pi}\sqrt{\frac{m_{wave-2}}{m_{wave-0}}}$$

$$f_{springing} = \frac{1}{2\pi}\sqrt{\frac{m_{springing-2}}{m_{springing-0}}}$$

where: m_{wave-0}, m_{wave-2} —— 0-th order moment and 2nd order moment of wave frequency component respectively;

$m_{springing-0}$, $m_{springing-2}$ —— 0-th order moment and 2nd order moment of springing component respectively.

The standard deviation of stress σ_i, the zero up-crossing frequency f_0 and the bandwidth correction factor of stress range $\lambda(m,\varepsilon)$ are to be calculated respectively as follows:

$$\sigma_i = \sqrt{m_{springing-0} + m_{wave-0}}$$

$$f_0 = \frac{\sqrt{f_{springing}^2 m_{springing-0} + f_{wave}^2 m_{wave-0}}}{\sigma_i}$$

$$\lambda(m,\varepsilon) = \frac{\nu_p}{\nu_c}\left[\lambda_H^{m/2+2}\left(1-\sqrt{\frac{\lambda_w}{\lambda_H}}\right) + \frac{m\Gamma\left(\frac{m}{2}+\frac{1}{2}\right)}{\Gamma\left(\frac{m}{2}+1\right)}\sqrt{\pi\lambda_w\lambda_H}\right] + \frac{\nu_w}{\nu_c}\lambda_w^{m/2}$$

where: $\nu_p = \lambda_H \nu_H \sqrt{1 + \frac{\lambda_w}{\lambda_H}\left(\frac{\nu_w}{\nu_H}\varepsilon\right)^2}$;

$\nu_c = \sqrt{\lambda_H \nu_H^2 + \lambda_w \nu_w^2}$;

$\lambda_H = \frac{m_{springing-0}}{\sigma_i^2}$;

$\lambda_w = \frac{m_{wave-0}}{\sigma_i^2}$;

$\nu_H = f_{springing}$;

$\nu_w = f_{wave}$;

$\varepsilon = \sqrt{1 - \frac{m_2^2}{m_0 m_4}}$.

3.1.2 Calculation of fatigue cumulative damage

The total fatigue damage, D_S, due to the wide-band stress response to wave frequency component and springing within the design fatigue life is to be calculated as follows:

$$D_S = \frac{T}{C}\left(2\sqrt{2}\right)^m \Gamma\left(1+\frac{m}{2}\right)\sum_{n=1}^{n_l}\sum_{j=1}^{n_s}\sum_{i=1}^{n_h}\left[\lambda_{nji} p_n p_j p_i f_{0,nji} \left(\sigma_{nji}\right)^m \mu_{nji}\right]$$

where: λ_{nji} —— bandwidth correction factor of stress response to wave frequency component of vertical wave bending moment or total bending moment in n-th loading condition, j-th sea state and i-th wave heading angle, to be calculated in accordance with $\lambda(m,\varepsilon)$ in 3.1.1(1) or 3.1.1(2) of this Chapter respectively;

$f_{0,nji}$ —— zero up-crossing frequencies, in Hz, of stress response to wave frequency component of vertical wave bending moment or total bending moment in n-th loading condition, j-th sea state and i-th wave heading angle, to be calculated in accordance with f_0 in 3.1.1(1) or 3.1.1(2) of this Chapter respectively;

σ_{nji} —— standard deviations, in N/mm^2, of stress response to wave frequency component of vertical wave bending moment or total bending moment in n-th loading condition, j-th sea state and i-th wave heading angle, to be calculated in accordance with σ_x in 3.1.1(1) of this Chapter or σ_i in 3.1.1(2) of this Chapter respectively;

$$\mu_{nji} = 1 - \frac{\Gamma\left[1+\frac{m}{2}, \nu_{nji}^2\right] - \nu_{nji}^{-\Delta m}\Gamma\left[1+\frac{m+\Delta m}{2}, \nu_{nji}^2\right]}{\Gamma\left[1+\frac{m}{2}\right]};$$

$$\nu_{nji} = \frac{S_Q}{2\sqrt{2}\sigma_{nji}}.$$

3.2 Contribution of linear springing to fatigue damage

3.2.1 Contribution of linear springing to fatigue damage, α_S, is to be calculated as follows and to be not less than zero:

$$\alpha_S = \frac{D_{total,S}}{D_{wave,S}} - 1$$

where: $D_{wave,S}$ ——fatigue cumulative damage due to stress response to wave frequency component of vertical wave bending moment (see 3.1.1(1) of this Chapter), to be calculated in accordance with 3.1.2 of this Chapter;

$D_{total,S}$ ——fatigue cumulative damage due to stress response to total vertical wave bending moment (see 3.1.1(2) of this Chapter), to be calculated in accordance with 3.1.2 of this Chapter.

3.3 Hull structure fatigue strength assessment taking into account linear springing

3.3.1 The influence factor of linear springing, f_{es}, is to be calculated as follows:

$$\alpha_S = f_{es}^m \cdot \frac{\Gamma\left(1+\frac{m}{\xi}\right) - \Gamma\left(1+\frac{m}{\xi}, \nu_{ts}\right) + \nu_{ts}^{-\left(\frac{\Delta m}{\xi}\right)} \cdot \Gamma\left(1+\frac{m+\Delta m}{\xi}, \nu_{ts}\right)}{\Gamma\left(1+\frac{m}{\xi}\right) - \Gamma\left(1+\frac{m}{\xi}, \nu_{ws}\right) + \nu_{ws}^{-\left(\frac{\Delta m}{\xi}\right)} \cdot \Gamma\left(1+\frac{m+\Delta m}{\xi}, \nu_{ws}\right)} - 1$$

where: α_S ——contribution of linear springing to fatigue damage, to be calculated in accordance with 3.2.1 of this Chapter:

$$\nu_{ts} = \left(\frac{S_Q}{f_{es} \cdot \Delta\sigma_{HG,WV}}\right)^{\xi} lnN_R;$$

$$\nu_{ws} = \left(\frac{S_Q}{\Delta\sigma_{HG,WV}}\right)^{\xi} lnN_R.$$

3.3.2 Hull structure fatigue strength assessment taking into account linear springing is to be carried out in accordance with CCS Guidelines for Fatigue Strength of Ship Structure. The adopted hull girder vertical bending moment used is to take the influence factor of linear springing, f_{es}, into consideration.

Chapter 4 Fatigue Strength Assessment of Hull Structure Subject to Whipping and Springing

4.1 Time history of stress response

4.1.1 In accordance with the requirements of 1.4.2 of Chapter 1, time history of hull girder vertical wave bending moment from non-linear time domain calculation is to be transferred to time history of stress at fatigue calculation point.

4.1.2 Load time history used for fatigue analysis is to have adequate statistical samples; generally one-hour time history is to be taken.

4.2 Calculation of fatigue damage

4.2.1 Fatigue cumulative damage due to wave frequency component of vertical wave bending moment

Rainflow counting method is applied in counting statistics of stress due to wave frequency component to obtain the stress range, $S_{w,k}$, and the corresponding number of stress cycles, $n_{nji}(S_{w,k})$, in each loading conditions, sea states and wave heading angles.

In combination with the S-N curve and the Palmgren-Miner linear cumulative damage rule, the fatigue damage, d_{nji}, in n-th loading condition, j-th sea state and i-th wave heading angle per unit time is to be calculated as follows:

$$d_{nji,w} = \sum_{k=1}^{n_{S,w}} \frac{n_{nji}(S_{w,k})}{N(S_{w,k}) \cdot t_{nji,w}}$$

where: $n_{nji}(S_{w,k})$ ——cycle number of the k-th stress range, $S_{w,k}$, in the n-th loading condition, j-th sea state and i-th wave heading angle;

$N(S_{w,k})$ ——cycle number of fatigue failure corresponding to the stress range $S_{w,k}$ obtained from S-N curve;

$n_{S,w}$ ——number of stress ranges in the n-th loading condition, j-th sea state and i-th wave heading angle;

$t_{nji,w}$ —— fitting time for loads, in s, in the n-th loading condition, j-th sea state and i-th wave heading angle.

The fatigue cumulative damage, $D_{wave,t}$, due to wave frequency component at the calculation point is to be calculated as follows:

$$D_{wave,t} = T \sum_{n=1}^{n_l} \sum_{j=1}^{n_s} \sum_{i=1}^{n_h} p_n p_j p_i d_{nji,w}$$

4.2.2 Fatigue cumulative damage due to total bending moment

Rainflow counting method is applied in counting statistics of stress due to total bending moment to obtain the stress range, $S_{t,k}$, and the corresponding number of stress cycles, $n_{nji}(S_{t,k})$ in each loading conditions, sea states and wave heading angles.

In combination with S-N curve and Palmgren-Miner linear cumulative damage rule, the fatigue damage, $\mathrm{d_{nji}}$, in n-th loading condition, j-th sea state and i-th wave heading angle per unit time is to be calculated as follows:

$$d_{nji,t} = \sum_{k=1}^{n_{S,t}} \frac{n_{nji}(S_{t,k})}{N(S_{t,k}) \cdot t_{nji,t}}$$

where: $n_{nji}(S_{t,k})$ ——cycle number of the k-th stress range, $S_{t,k}$, in the n-th loading condition, j-th sea state and i-th wave heading angle;

$N(S_{t,k})$ ——cycle number of fatigue failure corresponding to the stress range $S_{t,k}$ obtained from S-N curve;

$n_{S,t}$ ——number of stress ranges in the n-th loading condition, j-th sea state and i-th wave heading angle;

$t_{nji,t}$ ——fitting time for loads, in s, in the n-th loading condition, j-th sea state and i-th wave heading angle.

The fatigue cumulative damage, $D_{total,t}$, due to total bending moment at the calculation point is to be calculated as follows:

$$D_{total,t} = T \sum_{n=1}^{n_l} \sum_{j=1}^{n_s} \sum_{i=1}^{n_h} p_n p_j p_i d_{nji,t}$$

4.3 Contribution of whipping and springing to fatigue damage

4.3.1 Contribution of whipping and springing to fatigue damage, α_{WS}, is to be calculated as follows and to be not less than zero:

$$\alpha_{WS} = \frac{D_{total,t}}{D_{wave,t}} - 1$$

where: $D_{wave,t}$ ——fatigue cumulative damage due to stress response to wave frequency component of vertical wave bending moment, to be calculated in accordance with 4.2.1 of this Chapter;

$D_{total,t}$ ——fatigue cumulative damage due to stress response to total vertical wave bending moment, to be calculated in accordance with 4.2.2 of this Chapter.

4.4 Hull structure fatigue strength assessment taking into account whipping and springing

4.4.1 The influence factor of whipping and springing, f_{ews}, is to be calculated as follows:

$$\alpha_{WS} = f_{ews}^{m} \cdot \frac{\Gamma\left(1+\frac{m}{\xi}\right) - \Gamma\left(1+\frac{m}{\xi}, \nu_{tws}\right) + \nu_{tws}^{-\left(\frac{\Delta m}{\xi}\right)} \cdot \Gamma\left(1+\frac{m+\Delta m}{\xi}, \nu_{tws}\right)}{\Gamma\left(1+\frac{m}{\xi}\right) - \Gamma\left(1+\frac{m}{\xi}, \nu_{ws}\right) + \nu_{ws}^{-\left(\frac{\Delta m}{\xi}\right)} \cdot \Gamma\left(1+\frac{m+\Delta m}{\xi}, \nu_{ws}\right)} - 1$$

where: α_{WS} ——contribution of whipping and springing to fatigue damage, to be calculated in accordance with 4.3.1 of this Chapter;

$\nu_{tws} = \left(\frac{S_Q}{f_{ews} \cdot \Delta\sigma_{HG,WV}}\right)^{\xi} lnN_R$;

$\nu_{ws} = \left(\frac{S_Q}{\Delta\sigma_{HG,WV}}\right)^{\xi} lnN_R$.

4.4.2 Hull structure fatigue strength assessment taking into account whipping and springing is to be carried out in accordance with CCS Guidelines for Fatigue Strength of Ship Structure. The adopted hull girder vertical bending moment used is to take the influence factor of whipping and springing, f_{ews}, into consideration.

Chapter 5 Ultimate Strength Assessment of Hull Girder Subject to Whipping

5.1 Time history of vertical wave bending moment

5.1.1 In accordance with the process of 1.4.3 of Chapter 1, for vertical wave bending moment, non-linear time domain calculation in short-term sea states is to be adopted, and the time history of whipping bending moment and time history of rigid body non-linear bending moment without regard to whipping are to be calculated at the same time.

5.1.2 Load time history used for extreme value analysis is to have adequate statistical samples; generally 3-hour time history is to be taken.

5.2 Extreme value analysis of vertical wave bending moment

5.2.1 Weibull distribution parameters are fitted to peak values of vertical wave bending moment in various short-term sea states from non-linear time domain calculations and its cumulative distribution function, $F_0(x)$, is to be calculated as follows:

$$F_0(x) = 1 - e^{-\left(\frac{x-\delta}{\eta}\right)^{\beta}}$$

where: η —— scale parameter;

β —— shape parameter;

δ —— location parameter, preferably $\delta = 0$.

5.2.2 For vertical wave bending moment, the exceedance probability of long-term extreme values, $Q(x)$, is to be taken as 10^{-8} and the corresponding extreme value is to be calculated as follows:

$$Q(x) = P\{X \geq x\} = \sum_i \sum_j p_j p_i (1 - F_{0ji}(x))$$

where: X —— the extreme value of vertical bending moment at the exceedance probability;

$F_{0ji}(x)$ —— cumulative distribution function for the peak value of vertical wave bending moment in the j-th sea state and i-th wave heading angle, to be calculated in accordance with 5.2.1 of this Chapter.

5.3 Hull girder ultimate strength assessment taking into account whipping

5.3.1 The ultimate bending capacity of any hull girder section is to satisfy the following requirements:

$$\gamma_s M_s + \gamma_{whip} f_{whip} M_w \leq \frac{M_U}{\gamma_R}$$

where: M_s —— permissible still water bending moment, in kNm, to be calculated in accordance with provisions for relevant ship types in CCS rules;

M_w —— vertical wave bending moment, in kNm, to be calculated in accordance with provisions for relevant ship types in CCS rules;

M_U —— vertical hull girder ultimate bending capacity, in kNm, to be calculated in accordance with provisions for relevant ship types in CCS rules;

γ_s, γ_R —— partial safety factor for the still water bending moment and the hull girder ultimate capacity , to be taken in accordance with provisions for relevant ship types in CCS rules;

γ_{whip} —— partial safety factor for the impact of whipping bending moment, to be taken as:

$\gamma_{whip} = 1.05$;

f_{whip} —— whipping correction factors for hogging and sagging, to be calculated respectively as follows:

$$f_{whip} = C_{un} \frac{M_{whip}}{M_{nonl}}$$

where: M_{whip} —— the extreme values of whipping hogging bending moment or sagging bending moment, to be calculated in accordance with 5.2.2 of this Chapter;

M_{nonl} —— the extreme values of rigid body non-linear hogging bending moment or sagging bending moment without regard to whipping effect, to be calculated in accordance with 5.2.2 of this Chapter;

C_{un} —— the correction factor taking into account operating condition simplification, random waves and other uncertainties in calculation, to be taken as:

$C_{un} = 1.154$.

Appendix Numerical Model of Damping

1 Roll damping model

1.1 In the process of ship seakeeping calculation, additional damping forces are to be added to the motion equation in order to simulate the viscous roll damping and roll damping action due to various appendages. For non-linear roll damping, the model comprising linear damping coefficient and quadratic damping coefficient may be established as follows:

$$B_{44} = B_1 + B_2|\dot{\xi}_4| = \left(b_1 + b_2\frac{|\dot{\xi}_4|}{\omega_4}\right)B_4^{crit}$$

where: B_{44} —— roll damping;

B_1, B_2 —— linear damping coefficient and quadratic damping coefficient, respectively;

$\dot{\xi}_4$, ω_4 —— roll angular velocity and roll circular frequency respectively, in rad/s;

B_4^{crit} —— critical roll damping, to be calculated as follows:

$$B_4^{crit} = 1025 \cdot \Delta \cdot \mathrm{g} \cdot \frac{GM \cdot T_R}{\pi}$$

where: Δ —— ship displacement, in t;

GM —— initial metacentric height, in m;

T_R —— roll natural period, in s.

The critical damping value, B_4^{crit}, is to be non-dimensionalized. This model is determined by two coefficients, namely coefficient linearly correlated to the critical damping value, b_1, and quadratic coefficient related to angular velocity in roll, b_2. The linearised damping item and coefficient b_1 may be used when the problem is solved in linear frequency domain. Roll damping, B_{44}, could be based on experimental data or empirical methods. If no appropriate value is available, a linear damping of 5% of the roll critical damping is to be applied.

2 Structural damping model

2.1 In the calculation of hydroelasticity item, extra damping is to be added to the wave damping to take into account the impact of structural damping and cargo damping. The structural damping may vary between 1% and 3% of the critical damping and tends to increase for the higher vibration modes. The structural damping model is as follows:

$$B_{ii} = \eta_{ii}\frac{K_{ii}T_{ii}}{\pi}$$

where: B_{ii} —— additional damping for the vibration mode i;

K_{ii} —— total stiffness (hydrostatic + structural) for the vibration mode i;

T_{ii} —— natural period of vibration mode i;

η_{ii} —— fraction of the critical damping for the vibration mode i.

The addition of structural damping forces is to ensure a perfect equilibrium between the hydrodynamic forces and inertia forces in the calculated sections. Structural damping could be based on experimental data or empirical methods. If no appropriate value is available, η_{ii} may be taken as 1% for ballast condition and 3% for full load condition respectively.