



GUIDANCE NOTES ON

WHIPPING ASSESSMENT FOR CONTAINER CARRIERS

FEBRUARY 2014

**American Bureau of Shipping
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Foreword

The main purpose of these Guidance Notes is to supplement the Rules and Guides that ABS has issued for the Classification for container carriers. *ABS Rules for Building and Classing Steel Vessels (Steel Vessel Rules, or the Rules)* and the *ABS Guide for Application of Higher-Strength Hull Structural Thick Steel Plates in Container Carriers* require the evaluation of whipping effect on hull structures. These Guidance Notes address how to carry out such evaluations.

These Guidance Notes provide detailed procedures for the assessment of whipping loads and subsequent structure strength for container carriers. The technical background is based on the direct analysis of slamming load and structure dynamic response. These Guidance Notes are applicable to Container Carriers which have hull forms that can be susceptible to whipping effects.

The 2014 revision includes updated wave scatter diagram tables, details of closed form approach for whipping induced acceleration, and editorial changes.

The effective date of these Guidance Notes is the first day of the month of publication.

Users are advised to check periodically on the ABS website www.eagle.org to verify that the version of these Guidance Notes is the most current. Comments or suggestions can be sent electronically to rsd@eagle.org.

GUIDANCE NOTES ON WHIPPING ASSESSMENT FOR CONTAINER CARRIERS

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SECTION 1 Introduction

1 General

The design and construction of the hull, superstructure and deckhouses of container carriers are to be based on the applicable requirements of the ABS Rules and Guides. As a supplement to the ABS Rules and Guides, these Guidance Notes provide detailed procedures for whipping assessment for container carriers. The procedure is easy to use and can be utilized to make quick estimates of the whipping effect on hull girder bending moment and on fatigue load. It could be utilized during the conceptual design phase and to perform a sensitivity study of its variation with main dimensions and operational profiles. The technical background is based on the direct analysis of slamming load and structure dynamic response. The procedure has been calibrated using a number of existing designs.

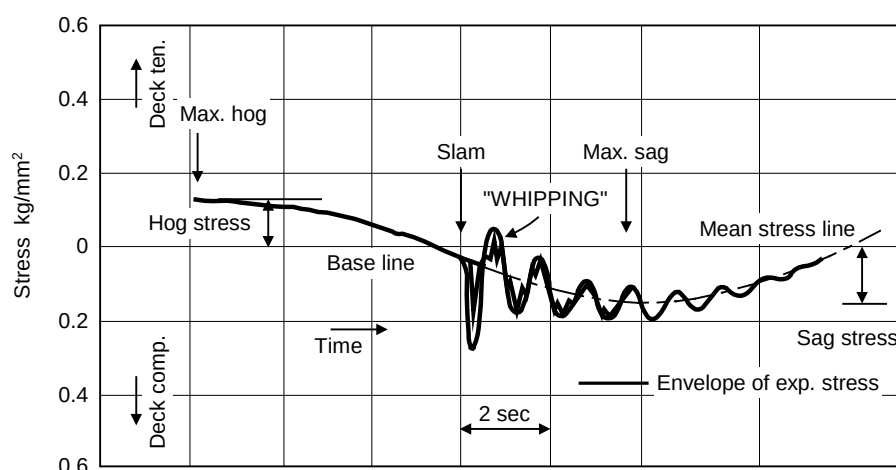
2 Whipping Phenomenon

In rough seas, the ship's bow and stern may occasionally emerge from a wave and re-enter the wave with a heavy impact or slam as the hull structure comes in contact with the water. A ship with such excessive motions is subject to very rapidly developed hydrodynamic loads. The ship will experience impulse loads with high-pressure peaks during the impact between the ship hull and water. Of interest are the impact loads such as bowflare slamming, bottom slamming, stern slamming, green water, and bow impact loads. These impact loads are of a transient nature and can cause severe structural damages.

Impact loads can cause local structural damage due to high impact pressure. They can also induce hull girder vibration mainly in the fundamental 2-node mode. This hull girder vibration is referred to as "whipping", as shown in Section 1, Figure 1. The vibratory hull girder bending stress, or whipping stress, is of much higher frequency than the wave-induced stress, and is effectively superimposed on it. The period of the fundamental mode of whipping is usually in the range from 0.5 to 2 sec.

Whipping has been observed in full scale measurements and can result in an increase of the extreme value of the hull girder bending moment and fatigue damage to structures.

FIGURE 1
Whipping Stress due to Slamming



For vessels possessing significant bowflare or operating at shallow draft, the impact load and the structure response to the impact load need to be evaluated accordingly. The *ABS Guide for Slamming Loads and Strength Assessment for Vessels* provides procedures for the assessment of the impact load and the structure strength due to impact pressures. These Guidance Notes focus on the hull girder response to the impact load, namely whipping effects.

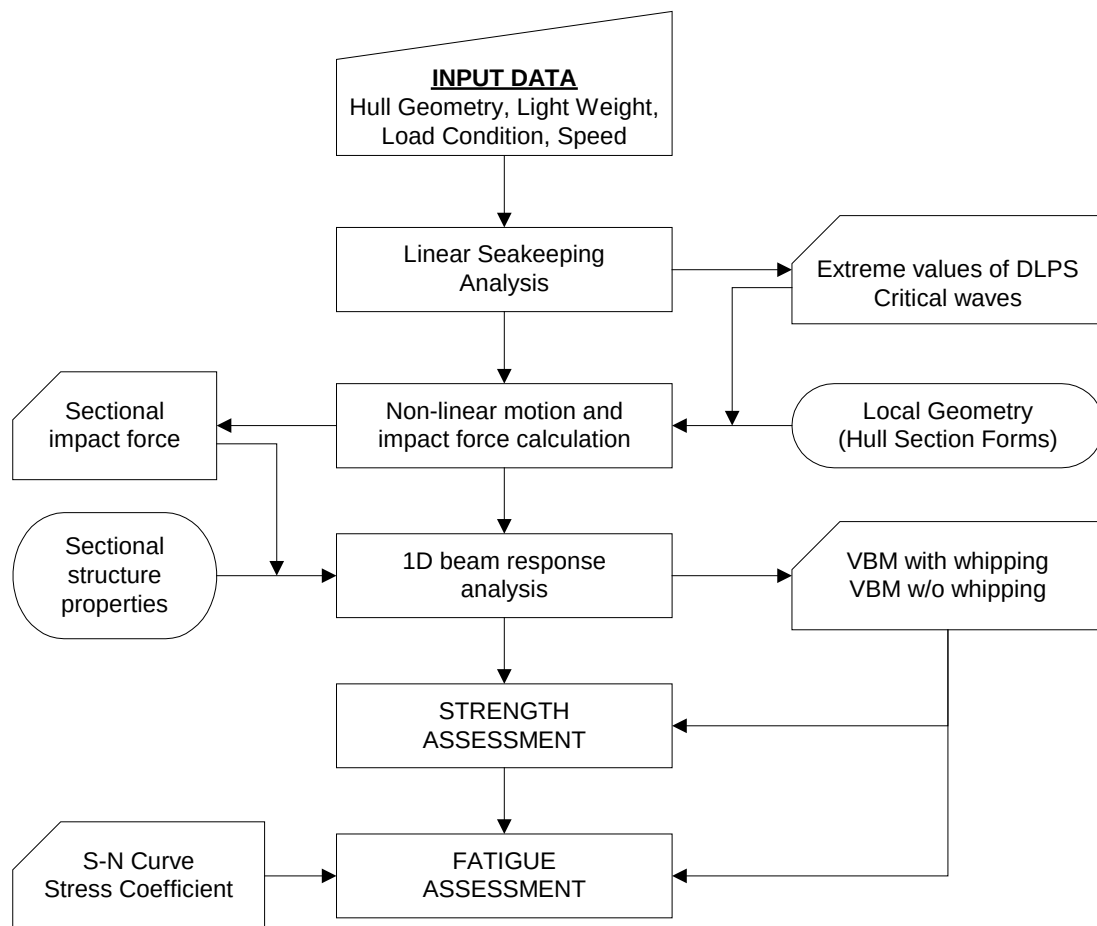
3 Whipping Assessment Procedure

The recommended whipping assessment procedure includes the following:

- Determine the critical loading conditions, forward speed, and operational headings for whipping assessment.
- Select wave environmental data, such as wave scatter diagram and wave spectrum.
- Perform vessel motion analysis.
- Calculate impact load.
- Calculate impact load induced hull girder bending moment.
- Calculate wave load induced hull girder bending moment.
- Determine total hull girder bending moment.
- Perform ultimate hull girder strength assessment.
- Determine whipping induced fatigue damage.
- Determine total fatigue damage.
- Calculate fatigue damage contribution from whipping.
- Calculate **whipping** induced acceleration

The analysis flowchart is given in Section 1, Figure 2. Detailed descriptions for the analysis procedures are given in Section 2 through Section 8.

FIGURE 2
Whipping Strength Assessment Procedure



SECTION 2 Loading Conditions, Speeds, and Headings

1 General

Impact loads are closely related to the relative motions between the vessel and the water surface. Loading condition, vessel's transit speed, and wave direction affect motions of the vessel and should be selected to cover the critical conditions for impact load and whipping response.

2 Critical Loading Conditions

In general, the critical loading conditions are to be identified based on the susceptibility of the hull structure to impact loads, giving consideration to the fore and aft hull forms, as well as the local drafts relative to the hull structure. Container carriers are, in general, susceptible to bowflare slamming due to large flare angles.

For the strength and fatigue assessment against whipping, two loading conditions are to be considered. One is the seagoing loading condition corresponding to the scantling draft, and the other is the seagoing condition with minimum draft.

3 Standard Speed Profile

In high seas, the ship speed may be reduced voluntarily or involuntarily. If a specific operation profile for the vessel is not available, a standard speed profile is to be applied based on the significant wave height as shown in Section 2, Table 1, where V_d is the design speed.

4 Wave Heading

It is assumed that whipping mainly occurs in bow sea conditions. It is recommended that wave headings of head sea (180-degree), 165-degree and 150-degree bow seas are to be included in the whipping analysis.

TABLE 1
Standard Speed Profile for Whipping Load Prediction (1 February 2014)

Significant Wave Height, H_s	Speed
$0 < H_s \leq 6.0 \text{ m (19.7 ft)}$	100% V_d
$6.0 \text{ m (19.7 ft)} < H_s \leq 9.0 \text{ m (29.5 ft)}$	75% V_d
$9.0 \text{ m (29.5 ft)} < H_s \leq 12.0 \text{ m (39.4 ft)}$	50% V_d
$12.0 \text{ m (39.4 ft)} < H_s$	25% V_d

SECTION 3 Wave Environments

1 Wave Scatter Diagram (1 February 2014)

As seagoing vessels are typically designed for unrestricted service, the following North Atlantic wave scatter diagrams are to be employed for strength and fatigue assessment, respectively. Section 3, Tables 1 and 2 show the wave scatter diagrams, where T_z is the average zero up-crossing wave period and H_s is the significant wave height. The numbers in the diagram represent the probability of sea states described as occurrences per 100,000 observations.

TABLE 1
North Atlantic Wave Scatter Diagram for Strength Evaluation (1 February 2014)

	T_z (sec)																
H_s (m)	3.5	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	Sum
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	1
15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0.0	0.0	3
14.5	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0.0	0.0	8
13.5	0.0	0.0	0.0	0.0	0.0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	0.7	0.2	0.1	0.0	21
12.5	0.0	0.0	0.0	0.0	0.1	1.0	4.4	9.9	12.8	11.0	6.8	3.3	1.3	0.4	0.1	0.0	51
11.5	0.0	0.0	0.0	0.0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1	124
10.5	0.0	0.0	0.0	0.0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4.0	1.2	0.3	0.1	285
9.5	0.0	0.0	0.0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	6.1	1.7	0.4	0.1	626
8.5	0.0	0.0	0.0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1	1309
7.5	0.0	0.0	0.0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1	2586
6.5	0.0	0.0	0.2	12.6	167.0	690.3	1257.9	1268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1	4806
5.5	0.0	0.0	1.0	51.0	498.4	1602.9	2372.7	2008.3	1126.0	463.6	150.9	41.0	9.7	2.1	0.4	0.1	8328
4.5	0.0	0.0	6.0	196.1	1354.3	3288.5	3857.5	2685.5	1275.2	455.1	130.9	31.9	6.9	1.3	0.2	0.0	13289
3.5	0.0	0.2	34.9	695.5	3226.5	5675.0	5099.1	2838.0	1114.1	337.7	84.3	18.2	3.5	0.6	0.1	0.0	19128
2.5	0.0	2.2	197.5	2158.8	6230.0	7449.5	4860.4	2066.0	644.5	160.2	33.7	6.3	1.1	0.2	0.0	0.0	23810
1.5	0.0	29.3	986.0	4976.0	7738.0	5569.7	2375.7	703.5	160.7	30.5	5.1	0.8	0.1	0.0	0.0	0.0	22575
0.5	1.3	133.7	865.6	1186.0	634.2	186.3	36.9	5.6	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	3050
Sum	1	165	2091	9280	19922	24879	20870	12898	6245	2479	837	247	66	16	3	1	100000

TABLE 2
North Atlantic Wave Scatter Diagram for Fatigue Evaluation (1 February 2014)

		Wave Period (sec)											Sum Over All Periods
		3.50	4.50	5.50	6.50	7.50	8.50	9.50	10.50	11.50	12.50	13.50	
Wave Height (m)	0.5	8	260	1344	2149	1349	413	76	10	1			5610
	1.5		55	1223	5349	7569	4788	1698	397	69	9	1	21158
	2.5		9	406	3245	7844	7977	4305	1458	351	65	10	25670
	3.5		2	113	1332	4599	6488	4716	2092	642	149	28	20161
	4.5			30	469	2101	3779	3439	1876	696	192	43	12625
	5.5			8	156	858	1867	2030	1307	564	180	46	7016
	6.5			2	52	336	856	1077	795	390	140	40	3688
	7.5			1	18	132	383	545	452	247	98	30	1906
	8.5				6	53	172	272	250	150	65	22	990
	9.5				2	22	78	136	137	90	42	15	522
	10.5				1	9	37	70	76	53	26	10	282
	11.5					4	18	36	42	32	17	7	156
	12.5					2	9	19	24	19	11	4	88
	13.5					1	4	10	14	12	7	3	51
	>14.5					1	5	13	19	19	13	7	77
Sum over All Heights		8	326	3127	12779	24880	26874	18442	8949	3335	1014	266	100000

2 Wave Spectrum

Sea wave conditions are to be modeled by the two-parameter Bretschneider spectrum, which is determined by the significant wave height and the zero-crossing wave period of a sea state. The wave spectrum is given by:

$$S_{\zeta}(\omega) = \frac{5\omega_p^4 H_s^2}{16\omega^5} \exp\left[-1.25(\omega_p / \omega)^4\right]$$

where

$$\begin{aligned} S_{\zeta} &= \text{wave energy density, m}^2\text{-sec (ft}^2\text{-sec)} \\ H_s &= \text{significant wave height, m (ft)} \\ \omega &= \text{angular frequency of wave component, rad/sec} \\ \omega_p &= \text{peak frequency, rad/sec} \\ &= 2\pi/T_p \\ T_p &= \text{peak period, sec} \\ &= 1.408 T_z \end{aligned}$$

To consider short-crested waves, “cosine squared” spreading is to be utilized, which is defined as:

$$f(\beta) = k \cos^2(\beta - \beta_0)$$

where

β = wave heading, following sea is 0 degrees, and head sea is 180 degrees, in the range of

$$\beta_0 - \frac{\pi}{2} \leq \beta \leq \beta_0 + \frac{\pi}{2}$$

β_0 = main wave heading of a short-crested wave

k = factor determined such that the summation of $f(\beta)$ is equal to 1.0, i.e.:

$$= \sum_{\beta_0 - \pi/2}^{\beta_0 + \pi/2} f(\beta) = 1$$

SECTION 4 Vessel Motions

1 General (1 February 2014)

This Section describes prediction of vessel motions. The motions of interest for slamming load calculations are relative velocity and relative motion in the vertical direction between waves and the part of the vessel subject to wave impact.

Vessel motions may be obtained either by model testing or through seakeeping analysis. A three-dimensional seakeeping analysis code is to be used for the motion and whipping analysis for final strength assessment. A **closed-form** motion calculation approach can also be utilized in the whipping assessment at an early design stage. The **closed-form** motion calculation will combine with the impact load and whipping analysis approach specified in Section 5. The **closed-form** analysis approach is easy to use and requires only main particulars of the design. It could be used during conceptual design for sensitive analysis and be used to narrow down critical cases for further study.

2 Closed-form Motion Calculation Approach (1 February 2014)

The closed-form expressions for the frequency response function for wave induced motions for monohull ships have been derived by Jensen and Mansour (2004). The closed-form expressions can be used to predict motions and relative motions at an early design stage.

2.1 Motions

The frequency response functions for heave and pitch for the vertical wave-induced motions of a homogeneously loaded box-shaped vessel can be derived analytically by the linear strip theory (Gerritsma and Beukelman, 1964). The equations of motion in regular waves with amplitude, a , can be written as (Jensen, 2001):

$$2 \frac{kd}{\omega^2} \ddot{w} + \frac{A^2}{kB\alpha^3 \omega} \dot{w} + w = aF \cos(\omega_e t)$$

$$2 \frac{kd}{\omega^2} \ddot{\theta} + \frac{A^2}{kB\alpha^3 \omega} \dot{\theta} + \theta = aG \sin(\omega_e t)$$

where

- k = wave number, m^{-1} (ft^{-1})
- ω = wave frequency, rad/sec
- B, d = breadth and draft of the **vessel**, m (ft)

Differentiation with respect to time, t , is denoted by a dot. The frequency of encounter, ω_e , is given by:

$$\omega_e = \omega - kV \cos \beta = \alpha \omega$$

where

- V = forward speed, m/sec (ft/sec)
- β = heading angle (180° corresponding to head sea)
- α = $1 - (kV/\omega) \cos \beta$

The sectional hydrodynamic damping is modeled by the dimensionless ratio A between the incoming and diffracted wave amplitude through the approximation:

$$A = 2 \sin(0.5kBa^2) \exp(-kd\alpha^2)$$

The forcing functions F and G are given as:

$$F = Cf \frac{2}{k_e L} \sin\left(\frac{k_e L}{2}\right)$$

$$G = Cf \frac{24}{(k_e L)^2 L} \left[\sin\left(\frac{k_e L}{2}\right) - \frac{k_e L}{2} \cos\left(\frac{k_e L}{2}\right) \right]$$

where

$$f = \sqrt{(1 - kd)^2 + \left(\frac{A^2}{kB\alpha^3}\right)^2}$$

$$k_e = \text{effective wave number}$$

$$= |k \cos \beta|$$

$$C = \text{smith correction factor, approximated by:}$$

$$= \exp(-k_e d)$$

The heave and pitch RAOs can be calculated by:

$$RAO_{heave} = \eta |F|$$

$$RAO_{pitch} = \eta |G|$$

where

$$\eta = \left(\sqrt{(1 - 2kd\alpha^2)^2 + \left(\frac{A^2}{kB\alpha^2}\right)^2} \right)^{-1}$$

For the block coefficient, C_B , less than one, the breadth, B , is replaced by BC_B .

The RAOs for the vertical motion and velocity at a longitudinal position x from the center of gravity can be obtained as:

$$RAO_w(x) = \sqrt{RAO_{heave}^2 + x^2 RAO_{pitch}^2} \quad RAO_{vel} = \omega_e RAO_w(x)$$

2.2 Relative Motions

Relative vertical motion $r(x, t)$ with respect to the wave elevation $h(x, t)$ can be expressed as:

$$r(x, t) = w(t) - x\theta(t) - h(x, t)$$

The relative motion at a position x is measured positively from amidships, and its RAO can be derived as:

$$RAO_r = \sqrt{(RAO_{heave} - \cos \xi(x))^2 + (xRAO_{pitch} + \sin \xi(x))^2}$$

where

$$\xi(x) = \varepsilon_e + \varepsilon_r + k_e x$$

ε_e and ε_r are defined by:

$$\begin{aligned}\cos \varepsilon_e &= \frac{1 - kd}{f} & \sin \varepsilon_e &= \frac{A^2}{kB\alpha^3 f} \\ \cos \varepsilon_r &= (1 - 2kd\alpha^2)\eta & \sin \varepsilon_r &= -\frac{A^2}{kB\alpha^2} \eta\end{aligned}$$

where the symbols have the same definition as in 4/2.1. The frequency response function for the relative velocity is obtained by multiplication with ω_e to the relative motion.

2.3 Short-term Statistics

The standard deviation, S_R , of a linear wave-induced response, R (Motions, relative motions, etc.), is given as:

$$S_R^2 = \int_0^\infty RAO_R^2(\omega) S(\omega) d\omega$$

where $S(\omega)$ is wave spectra.

3 Three-dimensional Seakeeping Analysis Method

For the final strength assessment of whipping effects, three-dimensional seakeeping analysis is to be applied to determine vessel motions. The seakeeping analysis can be carried out using the frequency domain or time domain approach. In the frequency domain analysis approach, the equations of motion are linearized by assuming the motions to be small and time harmonic. The boundary-value problem is solved using a singularity distribution on the mean body boundary.

An alternative to the frequency domain seakeeping analysis approach is to formulate the time domain initial-value problem. Non-linear effects can be included in time domain analysis approach. It is also convenient using a time domain program to link to the impact load and whipping calculation since they are calculated in time domain due to their transient nature and nonlinearity.

In general, the frequency domain analysis approach is less time consuming compared with the time domain analysis approach. A full spectrum analysis for motions and global hull girder response can be carried out using the frequency domain analysis approach for all wave conditions. The time domain approach can be used for the critical wave conditions.

3.1 General Modeling Considerations

In seakeeping analysis, the wetted body surface is to be partitioned into discrete panels to represent a smoothed body surface. In general, the panel mesh should be fine enough to resolve radiation and diffraction waves with reasonable accuracy.

When generating the panels, care should be taken on the smooth transition of the geometry and the size of the panels. The seakeeping analysis model includes the panel model and the characteristics of weight and waves. For a time domain analysis, free surface is also described using a number of panels.

For each loading condition, the draft at the F.P. and A.P., the location of center of gravity, radii of gyration, and sectional mass distribution along the vessel's length are to be prepared from the Trim and Stability booklet. The free surface GM correction is to be considered for partially filled tanks. For a tank with filling levels above 98% or below 2% of tank height, the free surface GM correction may be ignored.

The evaluation of the seakeeping analysis model should include the following:

3.1.1 Hydrostatic Balance (1 February 2014)

For each cargo loading condition, the hydrostatics of the vessel calculated based on the panel model are to be verified. At a statically balanced loading condition, the displacement, trim and draft, Longitudinal Center of Buoyancy (LCB), transverse metacentric height (GMT), longitudinal metacentric height (GML) and still water bending moment (SWBM) should be checked against the values provided in trim and stability booklet. The differences should be within the following tolerances:

Displacement:	±1%
Trim:	±0.1 degrees
Draft:	
Forward	±1 cm (0.4 in.)
Aft	±1 cm (0.4 in.)
LCB:	±0.1% of length
GMT:	±2%
GML:	±2%
SWBM:	±5%

3.1.2 Hydrodynamic Performance

Each software has its own requirements in term of the panel modeling size relative to wave length, smooth transition from the large panels to smaller panels, panel size near free surface, etc., that are to be adhered to. In general, there should be at least seven panel elements within the wave length. For very short waves, the panel model may not be able to meet that requirement but this does not, in general, affect the results significantly.

3.1.3 Roll Damping

The roll motion of a vessel in beam or oblique seas is greatly affected by viscous roll damping, especially with wave frequencies near the roll resonance. For seakeeping analysis based on potential flow theory, a proper viscous roll damping model is required. Experimental data or empirical methods can be used for the determination of the viscous roll damping. In addition to the hull viscous damping, the roll damping due to rudders and bilge keels is to be considered. If this information is not available, 10% of critical damping may be used for overall viscous roll damping.

3.2 Dominant Load Parameters

Frequency domain analysis is to be carried out for all wave conditions to determine the critical wave conditions for further time domain analysis. The critical wave conditions are determined based on the response of dominant load parameters. For the whipping assessment, the dominant load parameters are:

- Relative velocity at FP
- Relative velocity at AP
- Relative motion at FP
- Relative motion at AP
- Vertical bending moment at midship

In frequency domain analysis, the Response Amplitude Operators are first to be calculated for the dominant load parameters for loading conditions specified in Subsection 2/2 and all wave conditions. These dominant load parameters will be considered for the calculation of short-term and long-term analysis to determine the critical wave conditions.

A sufficient range of wave headings and frequencies should be considered for the calculation of the short-term extreme value of each relative velocity. The Response Amplitude Operators are to be calculated for wave headings from head seas (180 degrees) to following seas (0 degrees) in increments of 15 degrees. The range of wave frequencies is to include at least from 0.2 rad/s to 1.20 rad/s in increments of 0.05 rad/s.

3.3 Critical Wave Conditions

(1 February 2014) The critical wave conditions are determined based on the extreme values and response amplitude operator of dominant load parameters.

3.3.1 Extreme Value of Dominant Load Parameter

The extreme values of dominant load parameters can be predicted using a long-term analysis approach. The long-term analysis probability of the response exceeding x_0 , $\Pr\{x_0\}$ may be presented by the following equation, expressed as a summation of joint probability over the short-term sea states:

$$\Pr\{x_0\} = \sum_i \sum_j p_i p_j \Pr_j\{x_0\}$$

where

p_i = probability of the i -th main wave heading angle

p_j = probability of occurrence of the j -th sea state defined in the wave scatter diagram

$\Pr_j\{x_0\}$ = probability of the short-term response exceeding x_0 for the j -th sea state

For the calculation of long-term response of a vessel in unrestricted service, equal probability of main wave headings may be assumed for p_i . The long-term probability $\Pr\{x_0\}$ is related to the total number of response cycles in which the relative velocity is expected to exceed the value x_0 . Denoted by N , total number of cycles, the relationship between the long-term probability $\Pr\{x_0\}$ and N can be expressed by the following equation:

$$\Pr\{x_0\} = \frac{1}{N}$$

The term $1/N$ is often referred to as the exceedance probability level. Using the relationship given by the last equation, the response exceeding the value x_0 can be obtained at a specific probability level. The relevant value to be obtained from the long-term spectral analysis is the extreme value at the exceedance probability level of 10^{-8} . This probability level ordinarily corresponds to the long-term response of 20 ~ 25 years.

3.3.2 Critical Wave Conditions

The critical wave conditions are defined here as regular waves that simulate the long-term extreme values of the Dominant Load Parameters. The critical waves (or the equivalent design waves) can be characterized by wave amplitude, wave length, wave heading, and wave crest position referenced to amidships. For each of the Dominant Load Parameters, an equivalent design wave is to be determined.

3.3.2(a) Equivalent Wave Amplitude. The wave amplitude of the equivalent design wave is to be determined from the long-term extreme value of a Dominant Load Parameter under consideration divided by the maximum RAO amplitude of that Dominant Load Parameter. The maximum RAO occurs at a specific wave frequency and wave heading where the RAO has its maximum value. Equivalent wave amplitude (EWA) for the j -th Dominant Load Parameter may be expressed by the following equation:

$$a_w = \frac{LTR_j}{RAO_j^{\max}}$$

where

a_w = equivalent wave amplitude of the j -th Dominant Load Parameter, m (ft)

LTR_j = long-term response of the j -th Dominant Load Parameter

$RAO_j^{\max}$ = maximum RAO amplitude of the j -th Dominant Load Parameter

3.3.2(b) *Wave Frequency and Heading.* The wave frequency and heading of the equivalent design wave, denoted by (ω, β) , are to be determined from the maximum RAO of each Dominant Load Parameter. The wave length of the equivalent design wave can be calculated by the following equation:

$$\lambda = (2\pi g)/\omega^2$$

where

$$\begin{aligned}\lambda &= \text{wave length, m, (ft)} \\ g &= \text{gravitational acceleration, m/sec}^2 \text{ (ft/sec}^2\text{)} \\ \omega &= \text{wave frequency, rad/sec}\end{aligned}$$

3.4 Time Domain Analysis

For the selected critical waves, the ship motion analysis is to be performed in the time domain. The ship motions are to include all six degrees of freedom rigid-body motions. The hull may be assumed as a rigid body and the global rigid-body motion may not be altered by local slamming load. The time simulation is to be performed until the response reaches its steady state.

In the time domain analysis approach, the free surface is to be described by a number of panel elements covering a large area of the surface near the floating vessel. In general, there are two numerical methods for time domain analysis: mixed-source formulation and Rankine source formulation. Each approach has its own requirements on the area of the free surface that should be modeled in the analysis. Engineers should follow the recommendations from the user manual of the selected programs. In general, the Rankine source formulation approach may require a larger free surface domain than that of the mixed-source formulation approach.

From the time domain analysis, the six degrees of motions and the relative motions of the vessel to the waves are calculated. The time history of those motions will be utilized in the further impact load and whipping response predictions.

SECTION 5 Whipping Response – A Closed-form Method (1 February 2014)

1 General

Whipping is defined as a hull girder vibration induced by impact load. Whipping response includes the hull girder bending moments, hull girder shear force, hull girder deflection, hull girder acceleration, etc. These Guidance Notes focus on the response of vertical bending moment of container carriers.

This Section provides a closed-form method for the prediction of whipping response. The method can provide a rational prediction of the hull girder bending moments with sufficient engineering accuracy. At the conceptual design phase, the procedure can be used to make quick estimates and to perform sensitivity analyses by varying main dimensions and operation profiles.

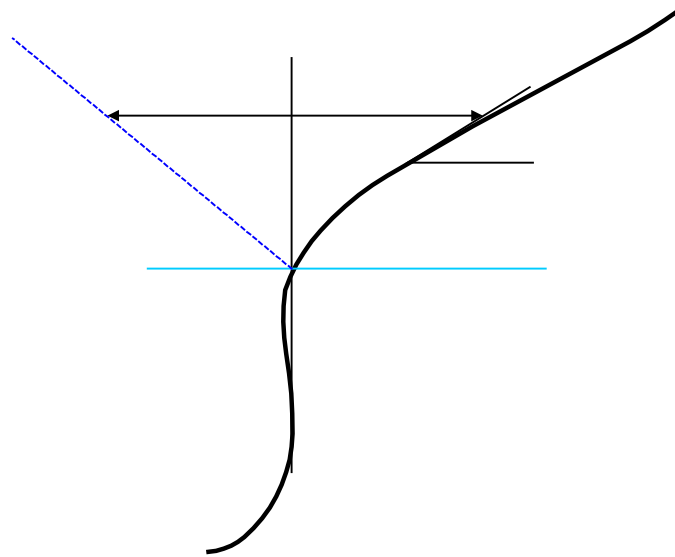
The required input information for the closed-form whipping assessment method includes the following main particulars as follows:

- Length of the vessel
- Molded breadth
- Draft for a selected loading condition
- Block coefficient
- Depth
- Bow-flare coefficient
- Local flare angle, breadth, and draft at location of impact
- 2-node modal natural period and relative damping
- Operational profile in terms of speed, heading and sea state
- Data for SN curve for fatigue damage estimation

2 Bowflare Impact Load

The impact load is closely related to the hull geometry and the relative velocity between the hull and water. The bowflare geometry can be approximately treated as a wedge (see Section 5, Figure 1).

FIGURE 1
Bowflare Geometry Model



The instantaneous impact force per unit length on a wedge can be predicted by a simplified formula as:

$$q(t) = 3C_p \rho g \dot{z}^3 t \quad \text{kN (tf, Ltf)}$$

where

$$\begin{aligned} C_p &= \frac{\pi^2}{4 \tan^2 \alpha} \\ \rho &= \text{density of sea water, t/m}^3 \text{ (Lt/m}^3\text{)} \\ g &= \text{acceleration of gravity, m/s}^2 \text{ (ft/s}^2\text{)} \\ \alpha &= \text{flare angle, rad} \\ \dot{z} &= \text{vertical relative velocity at the slamming location, m/sec (ft/sec)} \\ t &= \text{time measured from the wedge apex hitting the water, sec} \end{aligned}$$

For slamming, the time at maximum immersion including accounting for the water rise-up on a section with flare angle, α , and local breadth, B_ℓ , can be approximated by:

$$t_s = \frac{2}{3} \frac{B_\ell \tan \alpha}{2\dot{z}}, \text{ sec}$$

taking into account that the water rise-up is about half the immersion of the section according to the results shown by Zhao and Faltinsen (1993).

In this simple calculation formula, the important input parameter is the vertical position of the section which generates the bow flare slamming impact, or local breadth, B_ℓ , (see Section 5, Figure 2). The vertical position or local breadth will depend on impact velocity, bow flare angle and others. Numerical calibration may be needed to determine appropriate values.

To decide the local breadth, B_ℓ , the ship body can be assumed as a water entry of a two-dimensional wedge body. Local breadth can be calculated approximately by:

$$B_\ell = \frac{\Delta H}{\tan \alpha} \quad \text{m (ft)}$$

where

$$\Delta H = 0.75(\text{Depth} - \text{Draft}), \text{ m (ft)}$$

The local section at longitudinal location of $x = 0.95L$ can be selected to represent the slamming section. The **flare** angle, α , is measured for the wedge section four equal-distance points on the slamming section from the draft to 0.75 of the distance between the depth and draft (see Section 5, Figure 3). The average of these angles is the **flare** angle that will be used to calculate the local breadth.

FIGURE 2
Flare Angle and Local Breadth of Wedge Section (1 February 2014)

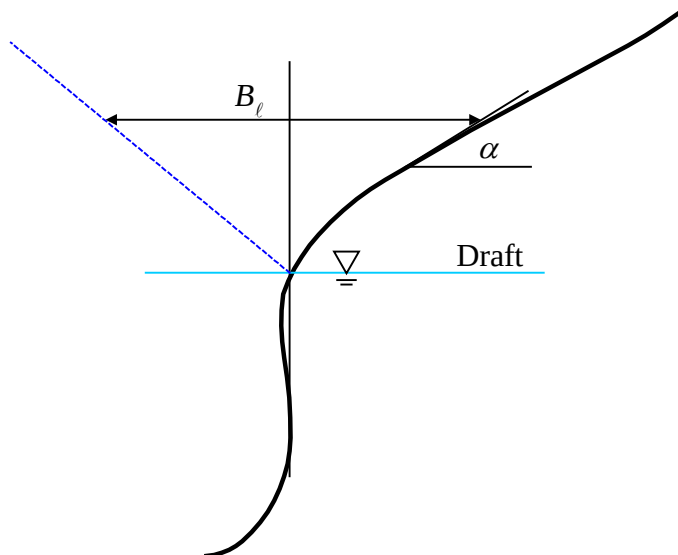
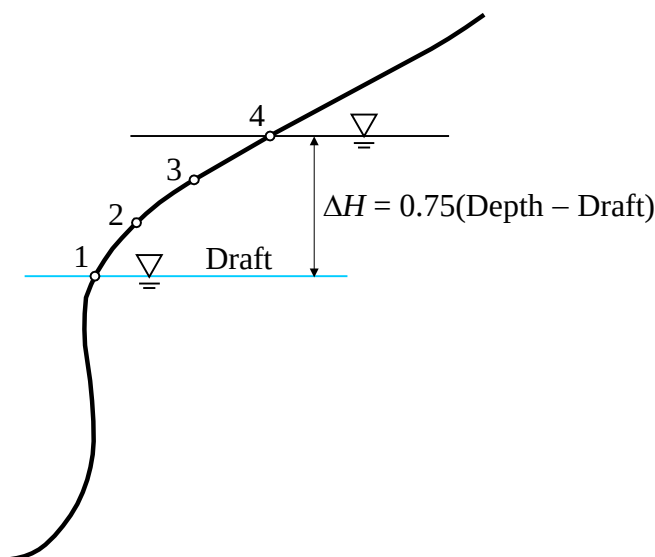


FIGURE 3
Calculation of Flare Angle and Local Breadth (1 February 2014)



3 Vertical Bending Moment and Shear Force due to Whipping

Full-scale measurements have shown that the whipping deflection is primarily in the form of the lower hull girder vibration mode, 2-node vertical vibration mode, in addition to heave and pitch. By using the 2-node mode in the calculation of the whipping bending moments and shear forces along the length of the vessel, an approximate solution for the whipping bending moment and shear forces at $X = x$ following a slam at $X = x_0$ can be derived by the modal superposition method.

3.1 Response of 2-Node Hull Girder Mode under Impact Loads

It is assumed that the duration of the impact is so short that it is not in resonance with heave and pitch modes. Using only the 2-node mode, the vertical whipping deflection of the beam can then be written:

$$u(x, t) = Cw(x)y(t)$$

where

$y(t)$ = response function of the normalized one degree-of-system under linear rising impact load

$w(x)$ = 2-node vibration mode shape

For a beam with tapered mass and stiffness properties towards the beam ends, the 2-node mode shape can be approximately written as:

$$w(x) = 7.95 \left(\frac{x}{L} \right)^3 - 1.23 \left(\frac{x}{L} \right)^2 - 4.58 \left(\frac{x}{L} \right) + 1 \quad 0 \leq \frac{x}{L} \leq 0.5$$

$$w\left(x + \frac{L}{2}\right) = w\left(\frac{L}{2} - x\right)$$

The mode shape is normalized such that $w(0) = 1$. Furthermore, it is assumed that the total inertia force and moment on the vessel are zero, i.e.:

$$\int_0^L m(x)w(x)dx = 0 \quad \int_0^L m(x)w(x)x dx = 0$$

where $m(x)$ is the mass per unit length. With the impact load, P , occurring at $x = x_0$ and with a longitudinal extend of β_L :

$$C = \frac{1}{\Omega^2 M_0} \int_0^L P(x)w(x)dx \cong P\beta_L \frac{w(x_0)}{\Omega^2 M_0}$$

$$M_0 = \int_0^L m(x)w^2(x)dx$$

The vertical bending moment after the impact load can be written as:

$$M_{whipping}(x, t) = P\beta_L \frac{S(x)}{M_0} w(x_0)y(t)$$

$$S(x) = \int_x^L m(u)w(u)(u - x)du$$

For a non-uniform beam, $S(x)$ can be described as:

$$\frac{S(x)}{LM_0} = -5.4 \left(\frac{x}{L} \right)^4 + 1.55 \left(\frac{x}{L} \right)^3 + 1.53 \left(\frac{x}{L} \right)^2 - 0.09 \left(\frac{x}{L} \right) \quad 0 \leq \frac{x}{L} \leq 0.5$$