Current Status of Second Generation Intact Stability Criteria Development and Some Recent Efforts

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ABSTRACT

The paper summarises the current status of the second generation intact stability criteria development for all five failure modes in the correspondence group established at SLF 55. Some points to be discussed in public are remarked and some recent works for them by the author are also presented. The discussion points includes that design measures for avoiding parametric roll of containerships and car carriers, safety levels of three layers and the methodology for excessive acceleration issues.

KEYWORDS

Parametric rolling, pure loss of stability, broaching, dead ship, excessive acceleration

INTRODUCTION

At the International Maritime Organization (IMO), the second generation intact stability criteria are now under development. These criteria are based on physics so that they are expected to be applicable to any ships in principle. Thus the use of new criteria could allow us to design completely new ships suitable for new era without empirical restrictions. The new criteria will be mandatory in the long run by being referred in the SOLAS and LL conventions for passenger and cargo ships of 24 meters or longer. (Francescutto and Umeda, 2010)

The second generation criteria deal with five failure modes: pure loss of stability in astern waves, parametric rolling, broaching, harmonic resonance under dead ship condition and excessive acceleration. For each failure mode, the first and second level vulnerability criteria and the direct stability assessment procedure as the third level will be developed. A ship is required to comply with one of the three criteria for each failure mode. Here the lower level criteria require smaller effort for the designer but with larger safety margin. In case the ship fails to comply with the second or third level criteria, operational limitation or guidance shall be developed based on the outcomes of the applied criteria

For pure loss of stability in astern waves, parametric rolling and broaching, the drafts of the first and second level criteria are agreed except for some remained items. For dead ship stability, consolidated proposal will be available for finalising the second level criteria. For excessive acceleration, it was confirmed that existing proposals cannot be used as they are now.

This paper summarises the current status of the second generation intact stability criteria development and presents some points to be discussed in public and recent works by the author for resolving the problems for realising the new criteria.

PURE LOSS OF STABILITY IN ASTERN WAVES

Roll restoring moment of a ship in longitudinal waves could be reduced when a wave crest is situated in the ship centre and the wave length is comparable to the ship length. In case of astern waves, the ship could start to roll as a result of the restoring reduction with low wave encounter and natural roll frequencies and then the roll induces additional hydrodynamic roll moment due to the unsymmetrical underwater hull shape. Based on the above mechanism of "pure loss of stability", the IMO agreed the first and second level criteria in principle. The current draft is set out as the Annex 2 (SLF 55/WP.3) with the square brackets which indicate undecided items.

First and second level criterion

In the first level criterion, the metacentric height, *GM*, in longitudinal waves is required to be positive in principle. If *GM* in longitudinal waves is sufficiently positive, most likely *GZ* in waves is sufficiently large. If *GM* in waves is negative with larger freeboard, *GZ* could be sufficient. Thus the requirement of *GM* could be more conservative.

The *GM* in longitudinal waves can be calculated by a simplified method except for tumblehome topside vessels. Here the moment of inertia of waterplane in waves can be approximated with that in calm water but with lowest draught. This is because the restoring reduction in longitudinal waves depends on mainly bow and stern parts, as shown in Fig. 1, so that we can ignore the effect of midship part for this purpose. As a result, the conventional hydrostatic curves are sufficient for the application of the first level criterion. This could avoid unnecessary increase of ship designers' loads because most of oil tankers and bulk carriers are not relevant to this failure mode at all.

In the second level, direct calculation of *GZ* in longitudinal waves is required for a ship but the Froude-Krylov approximation with static balance in sinkage and trim is used. Here three stability indices in one wave cycle shall be examined: the minimum *GM*, the largest loll and the smallest value of maximum *GZ*. However, it was agreed to exclude the *GM* because it is equivalent to non-existence of loll. As its alternative, one delegation proposed to use the angle of vanishing stability. The required value for the maximum *GZ* depending on the Froude number represents additional hydrodynamic roll moment due to the unsymmetrical underwater hull shape.

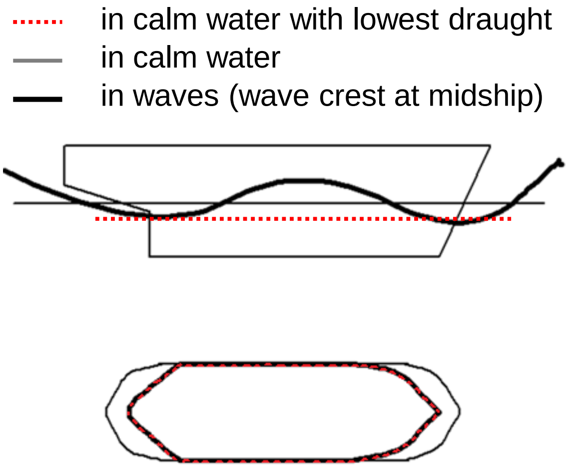

Fig. 1 Simplified estimation of restoring reduction on a wave crest.

For the reference wave heights and reference wave lengths, two candidates are available for final decision at the IMO. One is the 16 representative wave cases. The other is Grim's effective wave height (Grim, 1961) calculated for all possible significant wave heights and zero-crossing wave period appeared in the wave scattering diagram of the North Atlantic with the wave length equal to the ship length. Since the latter is more stringent than the former, the required probability (standard) of dangerous sea states should depend on the selection of reference waves as follows:

$$R_{PL0} = [0.06 \text{ in the former}]\ [\text{or } 0.15 \text{ in the latter}]\ .$$

Direct stability assessment

For the direct stability assessment, we can use numerical simulation of nonlinear roll motion coupled with manoeuvring motions (SLF 55/INF.15). Thus it is possible to identify the case that a ship having smaller maximum *GZ* could survive in realistic ocean waves with hydrodynamic effect other than the hydrostatic restoring moment.

PARAMETRIC ROLLING

The roll restoring variation in longitudinal waves could induce significant roll motion as a parametric roll resonance. The current draft is set out as the Annex 1 (SLF 55/WP.3) with the square brackets which indicate undecided items.

First level criterion

If we apply an averaging method or equivalent to the uncoupled roll model with sinusoidal *GM* variation and nonlinear roll restoring and damping moment, the amplitude of the parametric roll can be analytically determined (e.g. Sato, 1970). If the nonlinearities of roll restoring and damping are excluded, the occurrence condition of parametric roll can be obtained as

$$\frac{\Delta GM}{GM} > R_{PR} \quad . \qquad (1)$$

Here R_{PR} represents the linear roll damping for a steady state or the combination of the linear roll damping and wave group effect for a transient state.

In the first level criterion, the ΔGM can be calculated by a simplified method except for tumblehome topside vessels. Here the moment of inertia of waterplane in waves can be approximated with that in calm water but with lowest or highest draught. This is because the restoring variation in longitudinal waves depends on bow and stern parts, as shown in Fig. 1, so that we can ignore the effect of midship part for this purpose. As a result, the conventional hydrostatic curves are sufficient for the application of the first level criterion.

Here the roll damping is assumed to be always a constant regardless actual hull forms or to be a simple empirical estimate but depending on the area of bilge keel and bilge circle effect. And the wave steepness is assumed to be 0.0167.

Second level criterion

The second level criterion consists of two checks. A ship is requested to comply with one of them.

Its first check is based on the same methodology used in the first level criterion but direct calculation of *GM* in longitudinal waves and the examination with 16 wave cases are required. In addition, the effect of forward speed with related to wave and roll frequencies is included.

In its second check, the judgement is given with the calculation of amplitude of parametric roll in sinusoidal waves. Here direct calculation of *GM* in longitudinal waves and that of roll damping moment using the simplified version of Ikeda's semi-empirical method (Kawahara et al., 2009) or the equivalent are used. The *GZ* curve in calm water is fitted with a quintic formula and the damping is fitted with a cubic formula. In principle, the amplitude of parametric roll is calculated by using an averaging method. Alternatively, time domain numerical simulation could be used if the *GZ* curve is too complicated. The use of time domain numerical simulation for transient effect is also under discussion.

In this case, the used wave heights are Grim's effective wave height calculated for all possible significant wave heights and zero-crossing wave period appeared in the wave scattering diagram of the North Atlantic and the wave length is equal to the ship length. Thus, we can obtain the roll amplitude for all possible short-term sea states in the North Atlantic. Then the probability to meet dangerous sea states where the roll amplitude is greater than the critical angle can be calculated and is compared with the required value. If the ship fails to comply with this check, these data could be used for the operational limitation.

Direct stability assessment

For the direct stability assessment, we can use numerical simulation of nonlinear roll motion coupled with vertical motions. This approach allows us to take account of the effect of vertical motions on roll restoring variation. This effect could reduce the possibility of parametric roll. Thus the direct stability assessment is less conservative than the second level criteria.

BROACHING

Broaching is a phenomenon that a ship cannot keep a constant course even with the maximum steering effort. It often occurs when a ship is surf-ridded in following waves and the centrifugal force due to accelerated ship forward velocity and large yaw angular velocity could result in capsizing. Thus the first and the second criteria were agreed to use criteria for preventing surf-riding as shown in SLF 54/WP.3. Broaching itself could happen without surf-riding but the forward velocity is generally low so that danger for capsizing is not so high.

First level criterion

The first level criterion for broaching is already agreed at the IMO as follows. If the operational Froude number is larger than 0.3 and the ship length is smaller than 200 metres, the ship is judged as vulnerable to broaching. The former requirement is exactly the same as that in MSC/Circ. 707 developed in 1995, which was superseded as MSC.1/Circ. 1228. It is based on the smallest value of surf-riding threshold calculated by global bifurcation analyses of several ships with the wave steepness of 0.1 and the wave length to ship length ratio of 1 or over. The latter shows smaller possibility of occurrence of wave length of 200 metres or over.

Second level criterion

In the second level, direct estimations of surf-riding threshold for a given ship in sinusoidal waves are required. Here the Melnikov method (Kan, 1990; Spyrou, 2006) or equivalent as a global bifurcation analysis can be used. The wave conditions shall cover various wave heights and lengths. Then the short-term probability of surf-riding can be calculated with Longuet-Higgins (1983)'s theoretical formula of the joint probability density of local wave height and length. The long-term probability of surf-riding is required to be calculated with the wave scattering diagram in the North Atlantic and to be compared with acceptable value. At the IMO, the undecided items are only two: one is the value of acceptable probability and the other is a way for fitting calm-water resistance test data.

Direct stability assessment

For the direct stability assessment, we can use numerical simulation of nonlinear roll motion coupled with manoeuvring motions. Here we can discuss the danger of broaching directly. If the probability of stability failure due to broaching with associated with surf-riding is smaller than that of surf-riding, the direct stability assessment is less conservative than the second level criteria.

DEAD SHIP STABILITY

If a ship loses her propulsive power, the ship could suffer beam wind and waves as the worst case for harmonic resonance for longer duration. Or the ship master would select this situation for avoiding pure loss of stability, parametric rolling or broaching with possible operational guidance. Thus the ship designer shall guarantee the stability safety of ships under dead ship condition at least.

Its first level criterion was already agreed at the IMO as the current weather criterion but with the modified wave steepness table in MSC.1/Circ. 1200.

For the second level criterion, two proposals by two delegations were submitted: one is Method A and the other is Method B. Method A uses the linearisation of the *GZ* curve in the vicinity of the equilibrium heel angle under the action of mean wind. In order to estimate the failure probability, Method A utilises the concept of equivalent area. Given the actual critical heel angle (in general, if relevant, the minimum between the angle of progressive flooding, the angle of vanishing stability under the action of mean wind and a reference absolute critical angle, e.g. 50deg), Method A defines an equivalent critical heel angle in such a way that the area under the residual linearised *GZ* curve from the equilibrium heel angle up to the equivalent critical heel angle is the same as the area under the actual residual *GZ* curve from the equilibrium heel angle up to the actual critical heel angle. Method B approximates the original *GZ* curve with piece-wise linear curves. Here the maximum righting arm, the averaged slope of *GZ* curve up to the maximum righting arm and the angle of vanishing stability are kept in the approximation so that the area of approximated *GZ* curve up to the angle of vanishing stability is slightly smaller than that of the original *GZ* curve.

At the SLF 55 in 2013, however, these two delegations (SLF 55/3/11), as a result of their comparison study on two methods, submitted a consolidated proposal as follows:

- The level 2 vulnerability criterion should be based on the calculation of the weighted average total stability failure probability, considering a reference exposure time of one hour, taking into account all possible stationary sea states appearing in the reference wave scatter diagram with their respective probabilities of occurrence. Each stationary sea state is represented by the mean wind velocity, the significant wave height, the mean wave period, and the appropriate wind velocity spectrum and wave spectrum;

- Method A should be used because Method A provides outcomes similar to the simplified version of Method B and the use of Method A is simpler. For some stationary sea states having large total stability failure probability among them, the non-simplified version of Method B can be used as an alternative;

- The roll damping coefficient is to be calculated, as a basis, using the Ikeda's simplified method (Kawahara et al. 2009). However, methods which are deemed to be at least equivalently reliable can be used as well;

- The effective wave slope coefficient is to be calculated, as a basis, using an analytical approximate conservative formulation. However, methods which are deemed to be at least equivalently reliable can be used as well;

- The wind heeling moment including hydrodynamic reaction force is to be calculated, as a basis, similarly to the current weather criterion. However, methods which are deemed to be at least equivalently reliable can be used as well;

- For the determination of the parameters mentioned above, use can be made of model experiments or calculation methods which are deemed to provide a sufficient level of accuracy. When considering model experiments, the guidelines reported in MSC.1/Circ.1200 can be used as a basis.

EXCESSIVE ACCELERATION

If a ship has excessive *GM*, the natural roll period becomes very small so that excessive acceleration occurs at the wheel house and the cargo space. This excessive acceleration results in death or serious injury of crew and the cargo damage. For the first and second level criteria, two proposals were submitted to the correspondence group but the sample calculations using actual ships submitted to the correspondence group (SLF 55/3/1) reported that the maximum *GM* specified by these draft criteria can be smaller than the minimum *GM* specified by damage stability requirement.

Thus the correspondence group concluded that simple application of the existing draft criteria seems to be not feasible and SLF 55 agreed with this conclusion. Thus it is urgent to develop a new proposal on this failure mode.

DESIGN MEASURE FOR PARAMETRIC ROLLING

As an activity of the intersessional correspondence group on this issue, several delegations executed sample calculations of the level 1 and 2 criteria for parametric rolling and pure loss of stability using more than 150 sample ships in total (SLF 55/3/1). This number is comparable to those used for the current criteria of the 2008 IS Code Part A, i.e. the criteria regarding righting lever curve properties and the weather criterion. The sample ships used here includes oil tankers, chemical tankers, bulk carriers, LNG carriers, containerships, RoPax ships, car carriers, passenger ships, general cargo ships, reefers, offshore supply vessels, super yachts, fishing vessels and naval ships. The results indicate that most of oil tankers and bulk carriers comply with the level 1 criteria so that no problem exists for designing these ship-types. On the other hand, most of containerships and car carriers used in the submitted sample calculations fail to pass the level 2 parametric roll criterion.

Since the application of the direct stability assessment is not so easy, it is desirable for designers to resolve the failure problem for containership and car carriers within the stage of level 2. Therefore we have to explore ways to resolve it by design measures using the C11 class containership and a car carrier as examples. These sample ships do not comply with the level 2 criterion for parametric rolling.

Although several ways for reducing the danger of parametric rolling are available, effects of bilge keel area and allowable roll angle are presented in Figs. 2-3. Here the smallest values of the bilge keel area ratio among the symbols indicate the actual design. When the bilge keel area size increases or the allowable roll angle increases, the *C2* value of the level 2 criterion for parametric rolling decreases. If we keep 25 degrees as the allowable roll angle, very small increase of bilge keel size is sufficient to realise the compliance of the car carrier. This would result in only 0.4 per cent of propulsive power increase so that it could be a marginally acceptable solution. For the C11 class containership, however, this solution could result in 1.6 per cent of propulsive power increase so that it might not be feasible. If we adopt 30 degrees as the allowable roll angle by installing two-tiered lashing bridges, the power increase due to the bilge keel size increase could be 0.5 per cent so that it could not be impracticable.

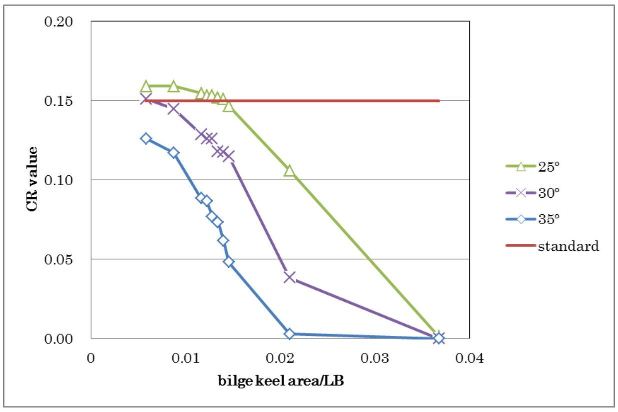

Fig.2 Effect of bilge keel area on *C2* value for the C11 class containership with different allowable roll angles. (Umeda et al., 2013)

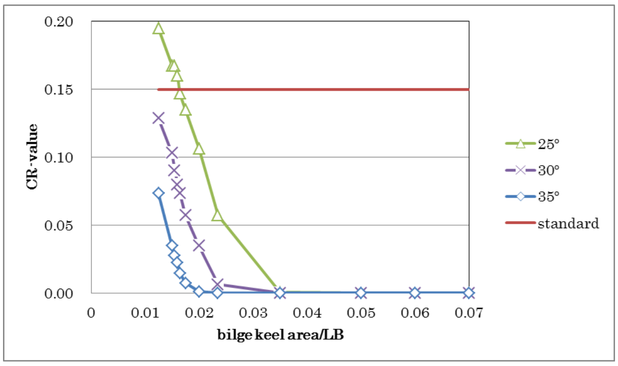

Fig.3 Effect of bilge keel area on *C2* value for the car carrier with different allowable roll angles. (Umeda et al., 2013)

VERIFICATION OF SAFETY LEVELS

Since the second generation intact stability criteria have three-layered structures, it is important to keep consistency of judgements among them. For the level 1 and 2 criteria for parametric rolling and pure loss of stability, sample calculation results using actual 35 ships covering both full and ballast conditions by a certain delegation (SLF 55/INF.15) reported that no 'false negative" case is found if the requirement of GM_{min} for CR1 of pure loss of stability is excluded and the effect of bilge keel is properly evaluated in the parametric roll level 1 criterion. For broaching, its sample calculation results using seven ships (SLF 55/3/12) also shows no "false negative" case if the required value is adequately selected. These consistencies are guaranteed with the systematic structure of the criteria and the adequate selection of required values. Here the sample calculations and the feedback from them are indispensable.

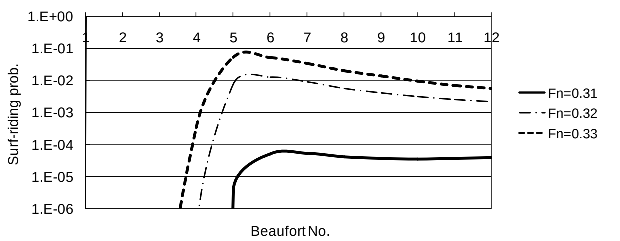

Fig. 4 Probabillity of surf-riding when the ITTC Ship A-2 meets a encounter wave cycle in pure following waves. (Umeda et al., 2008)

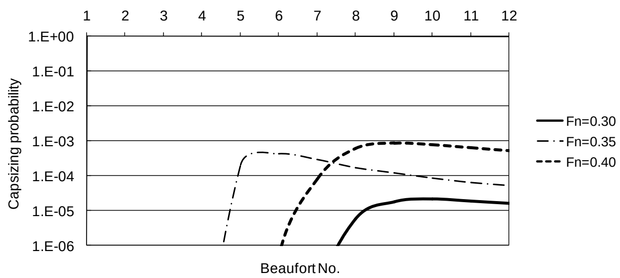

Fig. 5 Probabillity of stability failure due to broaching associated with surf-riding for the ITTC Ship A-2 in stern quartering waves with the desired course of 5 degrees from the wave direction. (Umeda et al., 2008)

Consistency between the level 2 criteria and direct stability assessment depends on the physics to be realised in different levels. For example, the broaching level 2 criterion requires the calculation of surf-riding probability and the direct stability assessment of broaching does that of probability of stability failure due to broaching associated with surf-riding. Figs. 4 and 5 demonstrate that the surf-riding probability is much larger than the probability of stability failure due to broaching associated with surf-riding (Umeda et al., 2008). Therefore, we can conclude that the broaching level 2 criterion is more conservative than the direct stability assessment for broaching.

METHODOLOGY FOR EXCESSIVE ACCELERATION

There are two different proposals for excessive acceleration but these specify wave conditions as wave steepness tables, i.e. the table in the current weather criterion or upper boundary of the wave scattering diagram. Considering the current situation in which the maximum allowable *GM*s by the current proposals could be occasionally smaller than the minimum allowable *GM* by the existing criteria, safety margin of the current proposals for excessive acceleration seems to be too large. Thus the use of operational limitation from the level 2 criterion could be a feasible approach. If so, it is worth while investigating the evaluation of acceleration at the wheel house for all possible significant wave height and zero-crossing period in the level 2 criterion for this mode.

CONCLUDING REMARKS

The main remarks from this work are summarized as follows:

(1) The level 1 and 2 criteria for pure loss of stability, parametric rolling and broaching are almost agreed at the IMO

except for some undecided items.

(2) For containerships and car carriers which fail to comply with the level 2 parametric rolling criterion, a feasible design measures could be provided.

(3) The level 1 criterion for dead ship stability was agreed at the IMO and the consolidated proposal for the level 2 dead ship stability criterion would be presented.

(4) For the level 2 criterion for excessive acceleration, a new proposal based on the wave scattering diagram is required for facilitating the use of operational limitation.

(5) The consistency among the different level requirements could be realised if we use systematic criterion structure in physics and adopt adequate required probability levels.

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ANNEX 1

PROPOSED AMENDMENTS TO PART B OF THE 2008 IS CODE TO ASSESS THE VULNERABILITY OF SHIPS TO THE PARAMETRIC ROLLING STABILITY FAILURE MODE

2.11 Ship assessment of vulnerability to the parametric rolling stability failure mode

2.11.1 Application

2.11.1.1 The provisions given hereunder apply to all ships of 24 meters and greater in length.

2.11.1.2 For all conditions of loading, a ship that:

.1 meets the standard contained in the criteria contained in 2.11.2 is considered not to be vulnerable to the parametric rolling stability failure mode;

.2 does not meet the standard contained in the criteria contained in 2.11.2 should be subject to more detailed assessment of vulnerability to the parametric rolling stability failure mode by applying the criteria contained in 2.11.3.

2.11.1.2 For each condition of loading, a ship that neither meets the criteria contained in 2.11.2 nor meets the criteria contained in 2.11.3 should be subject to either a direct stability assessment for the parametric rolling stability failure mode that is performed according to the specifications provided in Chapter [X] [or should follow the guidance to the master to avoid dangerous environmental conditions [provided in *operational limitation* document] [developed from the outcomes of the application of the criteria contained in 2.11.3]].[If criteria are not satisfied, the considered loading condition is subject to operational limitations, or direct stability assessment/operational guidance procedures, to the satisfaction of the Administration. (Refer to the guideline to be developed.)]

2.11.2 Level 1 Vulnerability Criteria for Parametric Rolling

2.11.2.1 A ship is considered not to be vulnerable to the parametric rolling stability failure mode if

$$\frac{\Delta GM}{GM} \leq R_{PR}$$

Where, R_{PR} = [0.5]

[or $0.17 + (2.125C_m - 1.7)\left(\frac{100A_{Bk}}{LB}\right)$; but the value of $\left(\frac{100A_{Bk}}{LB}\right)$ should not exceed 4 and the value of R_{PR} is 1.87 for a ship having sharp bilge.]

ΔGM = amplitude of the variation of the metacentric height as a longitudinal wave passes the ship calculated as provided in 2.11.2.2

Or $\Delta GM = \dfrac{I_H - I_L}{2V}$ only if $\dfrac{V_D - V}{A_W(D-d)} \geq 1.0$;
,

GM = metacentric height of the loading condition in calm water ;

A_{BK} = total overall area of the bilge keels (no other appendages), m^2;

L = Length between perpendiculars, m

B = moulded breadth of the ship, m;

D = moulded depth at side to the weather deck;

V_D = volume of displacement at waterline equal to D

A_W = waterplane area at the draft equal to d.

$$\left[\delta d_H = Min(D-d, \frac{L \cdot S_W}{2}) \right]$$

C_m = midship section coefficient;

d = draft corresponding to the loading condition under consideration;

$$d_H = d + \delta d_H ;$$

$$d_L = d - \delta d_L ;$$

I_H = moment of inertia of the waterplane at the draft d_H;

I_L = moment of inertia of the waterplane at the draft d_L;

V = volume of displacement corresponding to the loading condition under consideration;

$$\left[\delta d_L = Min(d - 0.25 d_{full}, \frac{L \cdot S_W}{2}) \right]$$

[d_{full} = draft corresponding to the full load condition]

$$S_W = 0.0167$$

[Whether Initial trim and free surface effect are taken into account or not should be specified.]

2.11.2.2 As provided by 2.11.2.1, ΔGM may be determined as half the difference between the maximum and minimum values of the metacentric height calculated for the ship, corresponding to the loading condition under consideration, considering the ship to be balanced in sinkage and trim on a series of waves with the following characteristics:

wavelength $\lambda = L$;

wave height $h = L \cdot S_W$; and

the wave crest centered at the longitudinal center of gravity
and at each 0.1L forward and aft thereof.

2.11.3 Level 2 Vulnerability Criteria for Parametric Roll

2.11.3.1 A ship is considered not to be vulnerable to the parametric rolling stability failure mode if the value of *C1* calculated according to paragraph 2.11.3.2 is less than R_{PR0} . If the value of C1 is larger than R_{PR0} but the value of *C2* calculated according to paragraph 2.11.3.3 is less than R_{PR1}, the ship is judged as non-vulnerable.

R_{PR0} and R_{PR1} is the standard that is the boundary between acceptable and unacceptable. [$R_{PR0} = 0.06$ or 0.1]

[$R_{PR1} = 0.15$ or 0.25]

2.11.3.2 The value for *C1* is calculated as a weighted average from a set of waves specified in 2.11.3.2.3.

$$C1 = \sum_{i=1}^{N} W_i C_i$$

Where, W_i = the weighting factor for the respective wave specified in 2.11.3.2.3;

C_i = 0, if the requirements of any of 2.11.3.2.1 and 2.11.3.2.2 are satisfied, and

= 1, if not.

2.11.3.2.1 The requirement for the variation of GM in waves is satisfied if, for each wave specified in 2.11.3.2.3:

$$GM(H_i, \lambda_i) > 0 \; and \; \frac{\Delta GM(H_i, \lambda_i)}{GM(H_i, \lambda_i)} < R_{PR} \quad ,$$

Where, R_{PR} = as defined in 2.11.2;

ΔGM(H_i, λ_i) = half the difference between the maximum and minimum values of the metacentric height calculated for the ship, corresponding to the loading condition under consideration, considering the ship to be balanced in sinkage and trim on a series of waves characterised by a *H*, and a λ_i;

$GM(H_i, \lambda_i)$ = the average value of the metacentric height calculated for the ship, corresponding to the loading condition under consideration, considering the ship to be balanced in sinkage and trim on a series of waves characterized by a *H*, and a λ_i ;

H_i = a wave height specified in 2.11.3.2.3; and

λ_i = a wave length specified in 2.11.3.2.3.

2.11.3.2.2 The requirement for the ship speed in a wave is satisfied if, for a wave specified in 2.11.3.2.3:

$$V_{PR\,i} > V_D$$

Where, VD = the [service /design] speed; and

VPR= the reference ship speed (m/s) corresponding to parametric resonance conditions, when $GM(H, \lambda i)>0$:

$$V_{PR\,i} = \left| \frac{2\lambda_i}{T_\phi} \cdot \sqrt{\frac{GM(H_i, \lambda_i)}{GM}} - \sqrt{g\frac{\lambda_i}{2\pi}} \right|$$

Where, T_ϕ = the roll natural period in calm water (s);

GM = the metacentric height in calm water (m);

$GM(H_i, \lambda_i)$ = as defined in 2.11.3.2.1;

λ_i = a wave length specified in 2.11.3.2.3; and

$|\ |$ = the absolute value operation/operand.

2.11.3.2.3 Specified wave cases for evaluation of the requirements contained in 2.11.3.2.1 and 2.11.3.2.2 are presented in Table 3-A-1. For use in 2.11.3.2, N is to taken as 16. In this table, W_i, H, λ_i are as defined in 2.11.3.2 and 2.11.3.2.1.

Table 3-A-1 Wave cases for parametric rolling evaluation

Case number i	Weight W_i	Wave length λ_i [m]	Wave height H_i [m]
1	1.300E-05	22.574	0.35
2	1.654E-03	37.316	0.495
3	2.091E-02	55.743	0.857
4	9.280E-02	77.857	1.295
5	1.992E-01	103.655	1.732
6	2.488E-01	133.139	2.205
7	2.087E-01	166.309	2.697
8	1.290E-01	203.164	3.176
9	6.245E-02	243.705	3.625
10	2.479E-02	287.931	4.04
11	8.367E-03	335.843	4.421
12	2.473E-03	387.44	4.769
13	6.580E-04	442.723	5.097
14	1.580E-04	501.691	5.37
15	3.400E-05	564.345	5.621
16	7.000E-06	630.684	5.95

2.11.3.3 The value for *C2* is calculated as a weighted average from a set of waves specified in 2.11.3.4.1, for different Froude numbers and for both head and following waves.

$$C2 = \sum_{i=1}^{N} W_i C_i$$

Where, W_i = the weighting factor for the respective wave specified in 2.11.3.4.1;

C_i = 1, if the roll angle specified in 2.11.3.4 exceeding [25] degrees, and

= 0, if not.

Then average of the above C2 values for different speeds and directions are used for judgement in 2.11.3.1.

2.11.3.4 Roll response, assessed as the maximum roll amplitude in head and following seas, is evaluated for a range of speeds in which the calculation of stability in waves is expected to account for influence of pitch and heave quasi-statically and the wave height, H_i, and the wave length, λ_I, are taken as specified in 2.11.3.4.1. In the absence of roll decay test data, roll damping may be modelled, using either simplified Ikeda's method or type-specific empirical data (with bilge keels geometry effect included), if appropriate.

[The roll response is determined using the roll motion equation according to one of three solution methods:

.1 *a numerical transient solution that provides evaluation of between four and eight waves in a wave group;*

.2 *an analytical steady state solution that may be applied only if both the angle of the maximum righting lever in calm water exceeds 30º and the deviation between a 5th degree polynomial fitting of the righting lever curve in calm water from upright to a heel angle of 30º and the actual righting lever curve does not exceed 5 per cent or 0.005m, whichever is greater, at each interval of 2º;*

.3 *a numerical steady state solution that is concluded only when the difference between successive maximum roll amplitudes is less than [0.5]º.*

[The details of the calculations methods (initial conditions, wave train amplitude) related to the transient and steady numerical approaches are to be developed intersessionally];

For each numerical solution, the righting lever curve at each position of the wave as it passes the ship is approximated by modulation of the calm water righting lever curve by the ratio of the instantaneous metacentric height to the calm water metacentric height.]

Roll response should be calculated with an equation of uncoupled roll motion. Here the following component s should be included:

- inertia term including added moment of inertia in roll in calm water;
- linear and nonlinear roll damping moment in calm water;
- linear and nonlinear roll restoring moment in calm water;
- wave effect on roll restoring moment.

The evaluation of roll amplitude should be carried out [either] by analytical [or numerical] method with reliable guidance for users] with the steady state roll amplitude [or the maximum roll angle within [4] roll cycles initiated with appropriate initial roll angle and roll angular velocity].

For calculating the roll amplitude [or the maximum roll angle] using the above formula, the following wavelength and wave height should be used:

Length $\lambda = L$

Height $h = 0.01 \cdot iL,\ \mathrm{i} = 0,1,...,10$

The Froude number of ship forward speed shall range from 0 to the service Froude number with the increment of [0.1]. For roll damping, the forward speed effect could be taken into account with Ikeda's method for lift component or equivalent.

2.11.3.4.1 Specified wave cases for evaluation of the requirements contained in 2.11.3.3 are presented in table 3-B-1. For use in 2.11.3.3, N is to taken as 306. For each combination of H_s and T_z, W_i is obtained as the value in table 3-B-1 divided by 100000, which is associated with a H_i calculated as provided in 2.11.3.4.2 and λ_i is taken as equal to L. Then the roll amplitude [or the maximum roll angle] for each H_i, should be interpolated from the relationship between h and the roll amplitude obtained in 2.11.3.4.

Table 3-B-1 Wave cases for parametric rolling evaluation

Hs/Tz	1.5	2.5	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
0.5	0.0	0.0	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
1.5	0.0	0.0	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
2.5	0.0	0.0	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
3.5	0.0	0.0	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
4.5	0.0	0.0	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
5.5	0.0	0.0	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
6.5	0.0	0.0	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
7.5	0.0	0.0	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
8.5	0.0	0.0	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
9.5	0.0	0.0	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
10.5	0.0	0.0	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
11.5	0.0	0.0	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
12.5	0.0	0.0	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
13.5	0.0	0.0	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
14.5	0.0	0.0	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
15.5	0.0	0.0	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
16.5	0.0	0.0	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
SUM:	0	0	1	165	2091	9280	19922	24879	20870	12898	6245	2479	837	247	66	16	3	1	100000

The Hs and Tz values are class midpoints.

2.11.3.4.2 The significant effective wave height, H_i, for use in evaluation of the requirements in 2.11.3.3 is calculated by filtering ocean waves within ship length. Here appropriate wave spectrum shape is assumed.

The details will be described in the explanatory note to be developed.

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ANNEX 2

PROPOSED AMENDMENTS TO PART B OF THE 2008 IS CODE TO ASSESS THE VULNERABILITY OF SHIPS TO THE PURE LOSS OF STABILITY FAILURE MODE

2.10 Assessment of ship vulnerability to the pure loss of stability failure mode

2.10.1 Application

2.10.1.1 The provisions given hereunder apply to all ships of 24 meters and greater in length for which the Froude number, F_N, corresponding to the service speed exceeds [0.2-0.31 or 0.26]. For the purpose of this section, F_N is determined for the following formula:

$$F_N = \frac{V_s}{\sqrt{gL}}$$

Where, Vs = Service speed [at 90%MCR], m/s

L = Ship length, m

g = acceleration due to gravity, 9.81 m/s^2

2.10.1.2 For all conditions of loading, a ship that:

.1 meets the standard contained in the criteria contained in 2.10.2 is considered not to be vulnerable to the pure loss of stability failure mode;

.2 does not meet the standard contained in the criteria contained in 2.10.2 should be subject to more detailed assessment of vulnerability to the pure loss of stability failure mode by applying the criteria contained in 2.10.3.

2.10.1.3 For each condition of loading, a ship that neither meets the criteria contained in 2.10.2 nor meets the criteria contained in 2.10.3 should be subject to either a direct stability assessment for the pure loss of stability failure mode that is performed according to the specifications provided in Chapter [X] [or should follow the guidance to the master to avoid dangerous environmental conditions [provided in *operational limitation* document] [developed from the outcomes of the application of the criteria contained in 2.10.3]].[If criteria are not satisfied, the considered loading condition is subject to operational limitations, or direct stability assessment/operational guidance procedures, to the satisfaction of the Administration (ref: guideline to be developed for passenger and cargo vessels.)]

(In explanatory note, importance of critical loading condition should be mentioned.)

2.10.2 Level 1 Vulnerability Criteria for Pure Loss of Stability

2.10.2.1 A ship is considered not to be vulnerable to the pure loss of stability failure mode if

$$GM_{\min} > R_{PLA}$$

Where, R_{PLA} = [min(1.83 d $(F_N)^2$, 0.05)] m; and

GM_{min} = the minimum value of the metacentric height [on level trim and without taking consideration of free surface effects] as a longitudinal wave passes the ship calculated as provided in 2.10.2.2, Or $GM_{\min} = KB + \frac{I_L}{V} - KG$ only if $\frac{V_D - V}{A_W(D-d)} \geq 1.0$;

,

d = draft corresponding to the loading condition under consideration;

I_L = moment of inertia of the waterplane at the draft d_L;

$d_L = d - \delta d_L$;

KB = height of the vertical centre of buoyancy corresponding to the loading condition under consideration;

KG = height of the vertical centre of gravity corresponding to the loading condition under consideration;

V = volume of displacement corresponding to the loading condition under consideration;

$$\left[\delta d_L = Min(d - 0.25 d_{full}, \frac{L \cdot S_W}{2})\right]$$

$$S_W = 0.0334$$

D = Depth

V_D = volume of displacement at waterline equal to *D*

A_W = waterplane area at the draft equal to *d.*

[If

$$\frac{V_D - V}{A_W(D-d)} < 1.0$$

,

in each case specified herein, the righting lever at a heel angle of 30 degrees must be positive.]

2.10.2.2 As provided by 2.10.2.1, $GM_{\min}$ may be determined as the minimum value calculated for the ship, corresponding to the loading condition under consideration, considering the ship to be balanced in sinkage and trim on waves with the following characteristics:

wavelength $\lambda = L$;

wave height $h = S_W L$; and

wave crest centred at the longitudinal centre of gravity and at each 0.1L forward and aft thereof.

2.10.3 Level 2 Vulnerability Criteria for Pure Loss of Stability

2.10.3.1 A ship is considered not to be vulnerable to the pure loss of stability failure mode if the maximum value of CR_1, CR_2, and CR_3, calculated according to paragraphs 2.10.3.2, 2.10.3.3, and 2.10.3.4 under the service speed, respectively, is less than R_{PL0}.

R_{PL0} is the standard that is the boundary between acceptable and unacceptable.

$$R_{PL0} = [0.06 \text{ in case Option6-A}] \text{ [or } 0.15 \text{ in case of Option6-B]}$$

(depending on future decision of the reference waves)

2.10.3.2 Each of the three criteria, CR_1, CR_2, and CR_3, represent a weighted average of certain stability parameters for a ship considered to be statically positioned in waves of defined height (H_i) and length (λ_i) obtained from table 2.10.3.2.

Where,

$$[CR_1 = \sum_{i=1}^{N} W_i C1_i = \textit{Weighted criterion } 1;]$$

$$CR_2 = \sum_{i=1}^{N} W_i C2_i = \textit{Weighted criterion } 2;$$

$$CR_3 = \sum_{i=1}^{N} W_i C3_i = \textit{Weighted criterion } 3; \tag{20}$$

W_i = a weighting factor obtained from Table [6-A-1 or 3-B-1];

N = number of wave cases for which $C1_i$, $C2_i$, $C3_i$ are evaluated =

[16 in case of Option 6-A, 306 in case of Option 6-B];

$C1_i$ = Criterion 1 evaluated according to 2.10.3.3;

$C2_i$ = Criterion 2 evaluated according to 2.10.3.4; and

$C3_i$ = Criterion 3 evaluated according to 2.10.3.5.

(CR_1 should be reformulated.)

Option 6-A

Table 6-A-1 Wave cases for pure loss of stability

Case number i	Weight W_i	Wave length λ_i [m]	Wave height H_i [m]
1	1.300E-05	22.574	0.7
2	1.654E-03	37.316	0.99
3	2.091E-02	55.743	1.715
4	9.280E-02	77.857	2.589
5	1.992E-01	103.655	3.464
6	2.488E-01	133.139	4.41
7	2.087E-01	166.309	5.393
8	1.290E-01	203.164	6.351
9	6.245E-02	243.705	7.25
10	2.479E-02	287.931	8.08
11	8.367E-03	335.843	8.841
12	2.473E-03	387.44	9.539
13	6.580E-04	442.723	10.194
14	1.580E-04	501.691	10.739
15	3.400E-05	564.345	11.241
16	7.000E-06	630.684	11.9

Option 6-B

For calculating the restoring moment in waves, the following wavelength and wave height should be used:

Length $\lambda = L$

Height $h = 0.01 \cdot iL,\ \mathrm{i} = 0,1,...,10$

Then the indexes for the Criterions [1]-3 are calculated with the above as described in 2.10.3.[3]-5.

Specified wave cases for evaluation of the requirements are presented in Table 3-B-1. For use in 2.10.3.[3]-5, N is to taken as 306. For each combination of H_s and T_z, W_i is obtained as the value in table 3-B-1 divided by 100000, which is associated with a H_i calculated below and λ_i is taken as equal to L. Then the indexes for each H_i, should be interpolated from the relationship between h and the indexes obtained above.

The 3 per cent largest effective wave height, H_i, for use in evaluation of the requirements is calculated by filtering ocean waves within ship length. Here appropriate wave spectrum shape is assumed.

The details will be described in the explanatory note to be developed.

2.10.3.3 ***Criterion 1***

[Criterion 1 is a criterion as provided in the following formula:

$$C1_i = \begin{cases} 1 & [\varphi_V > [R_{PL1}]; \\ 0 & otherwise \end{cases}$$

The angle of vanishing stability may be determined as the minimum value/calculated for the ship, corresponding to the loading condition under consideration, considering the ship to be balanced in sinkage and trim on a series of waves with the characteristics identified in table 2.10.3.2 and with the wave crest centred at the longitudinal centre of gravity and at each 0.1λ forward and aft thereof.

R_{PL1} = [30 degrees]]

2.10.3.4 ***Criterion 2***

Criterion 2 is a based on a calculation of the ship's angle of loll as provided in the following formula:

$$C2_i = \begin{cases} 1 & \phi_{loll}(\deg rees) > [R_{PL2}] \\ 0 & otherwise \end{cases}$$

ϕ_{loll} is a maximum loll angle determined from the righting lever curve calculated for the ship, corresponding to the loading condition under consideration, considering the ship to be balanced in sinkage and trim on a series of waves with the characteristics identified in table 2.10.3.2 and with the wave crest centered at the longitudinal center of gravity and at each 0.1L forward and aft thereof.

R_{PL2} = [25 degrees]

2.10.3.5 ***Criterion 3***

Criterion 3 is a based on a calculation of the maximum value of the righting lever curve as provided in the following formula:

$$C3_i = \begin{cases} 1 & GZ_{\max}(m) < [R_{PL3}] \\ 0 & otherwise \end{cases} \qquad (24)$$

GZ_{max} is determined as the smallest of maxima of the righting lever curves calculated for the ship, corresponding to the loading condition under consideration, considering the ship to be balanced in sinkage and trim on a series of waves with the characteristics identified in table in 2.10.3.2 and with the wave crest centered at the longitudinal center of gravity and at each 0.1λ forward and aft thereof.

R_{PL3} = [$8(H/\lambda)dF_N^2$].

**