NATIONAL TECHNICAL UNIVERSITY OF ATHENS

DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE ENGINEERING

DIVISION OF SHIP DESIGN AND MARITIME TRANSPORT

DIPLOMA THESIS

EVALUATION OF IMO'S "SECOND GENERATION INTACT STABILITY CRITERIA"

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ABSTRACT

International Maritime Organisation is currently developing Second Generation Intact Stability Criteria which aim to reduce the risk of certain forms of stability failure in waves. These failures include parametric rolling, pure loss of stability, surf-riding/broaching and excessive lateral accelerations. The first regulation draft was published by Sub – Committee on Ship Design and Construction in December 2014.

The purpose of this diploma thesis is to evaluate the current form of the regulation drafts by applying them on a sample of vessels and interpreting the results. Chapter IV is dedicated to pure loss of stability failure, Chapter V to parametric rolling, Chapter VI to surf-riding and Chapter VII to excessive accelerations. In the first subchapter of these chapters, the physical background of the investigated phenomena is analysed. Secondly, the draft regulation and the results from its application on a certain investigated ship are presented. In the last subchapter, the results are analysed and compared with the results from other methods or general knowledge. Moreover, conclusions are drawn regarding the credibility of the proposed regulations and their capability of actually measuring a ship's vulnerability to the investigated forms of instability. Finally, in Chapter VIII further future work is considered.

All calculations were carried out by using the programming environment of Wolfram Mathematica. The hulls of the investigated ships were modelled by using Maxsurf Modeller [18] software and their hydrostatic components, such as the GZ curve, were calculated by using Maxsurf Stability software [18].

CONTENTS

CHAPTER I

Introduction

Stability failure in rough seas has always been a great fear of seafarers around the globe. The constant efforts of the International Maritime Organisation and its regulatory actions have established an adequate level of safety, at least for large vessels, that makes events of capsizing due to beam seas highly improbable.

However the battle is not won yet. Modern designs and the pursuit of greater efficiency and finer hulls has led to forms of instability in waves that were a subject of academic interest in the past but could become the leading cause of accidents in the future. These forms of failure include parametric rolling, surf-riding and pure loss of stability. Moreover, excessive accelerations that take place in certain areas of a ship of great height during rough seas are a common cause for accidents that involve loss or damage of cargo and tipping of sailors.

While these instabilities do not usually cause capsizing directly on large vessels, other important hazards may occur. For instance, large roll angles due to parametric rolling are a cause for loss of containers in the sea. This was the case for APL China accident in 1998[19] and may be the case for many other container ships, such as Nedlloyd Genoa in 2006[16], JRS Canis in 2007[4] and Svendborg Maersk in 2014 [2] where existence of parametric rolling is probable but not confirmed. For smaller vessels, such as fishing vessels, those phenomena may cause more severe consequences. In 1986, fishing vessel Merry Jane heeled extremely in rough seas due to broaching which caused loss of life and injuries [31]. Many other fishing vessels may also be lost due to surf-riding [23]. Last but not least, excessive accelerations on bridge decks are a serious hazard for the crew, where lateral accelerations of 1.0g are possible, as in Chicago Express in 2009 where injuries and loss of life occurred [14].

As a result, IMO is currently developing the Second Generation Intact Stability Criteria. The purpose of these regulations is to reduce the risk that arises from these forms of failure and to ensure that their probability of taking place is adequately low. They target the faster vessels with fine hulls, such as container ships and Ro-Ro vessels which seem to be prone to accidents of this nature. According to the regulation drafts, the vulnerability of each vessel to each form of failure is evaluated by risk based methods that use a certain combination of empirical, statistical and differential equations in order to perform the required calculations.

After many years of discussions and preparations, the first draft of the Second Generation Intact Stability Criteria was published in December 2014 by Sub – Committee on Ship Design and Construction (SDC) in December 2014[13]. The work presented in this diploma thesis is based on the regulations formulated in this draft.

CHAPTER II

Historical Background

The roots of intact stability regulations can be traced back to the PhD thesis of Rahola [22]. His work involved statistical regression of the hydrostatic stability of 30 vessels that capsized in Baltic Sea and was the basis for Resolution A.167 for all ships in length less than 100m [8]. Resolution A.167 set the standards for hydrostatic stability. However, it was widely accepted that, dynamic stability failures could also occur under certain sea states and thus, the implementation of new criteria regarding dynamic stability were necessary. As a result, IMO introduced the Weather Criterion in 1985 as a part of Resolution A.562 [9].

Weather Criterion was the first attempt at setting standards based on scientific rather than empirical methods. The purpose of it is to ensure the ship's capability of remaining stable under extreme weather conditions, including severe wind and waves. The method used was deterministic and based on the works of Yamagata [32] and the Japanese standards or stability. It involved the calculation of a ship's rolling amplitude under a specific sea state taking into consideration the effects of both wind and a harmonic wave of specific characteristics. Despite the method being scientific, since it involves the solution of a non-linear differential equation, the values of the parameters of the problem occur from empirical calculations based on ships that are 30-35 years old.

In 1993, IMO adopted "Intact Stability Code" in an attempt to include all existing stability regulations in a single code. I.S. code was applicable to most ships with length greater than 24 metres [10]. In 2002, the intact stability Working Group was re-established by IMO's Subcommittee on Stability and Load Lines and on Fishing Vessels Safety (SLF) in order to revise IS code. As a result, the revised IS code was adopted in 2008[11].

In the 48h session of SLF in 2005, the Working Group expressed the necessity of second generation intact stability criteria which would address various forms of failure in waves, such as extreme variations of restoring arm and manoeuvring in waves. In the following years, the Working Group developed draft regulations regarding those forms of failure. In the most recent report of IMO's Sub-Committee on Ship Design (SDC) [13], regulation drafts are developed for four forms of failure in waves: Pure Loss of Stability, Parametric Rolling, Surf-Riding and Excessive Accelerations. This work is based on those drafts which are currently still in development.

CHAPTER III

Concept of Second Generation Intact Stability Criteria

Second Generation Intact Stability Criteria are to be included in Chapter 2.3 of I.S. Code as an extension of the Weather Criterion. They will use a multi-tiered approach as shown in Figure 1.

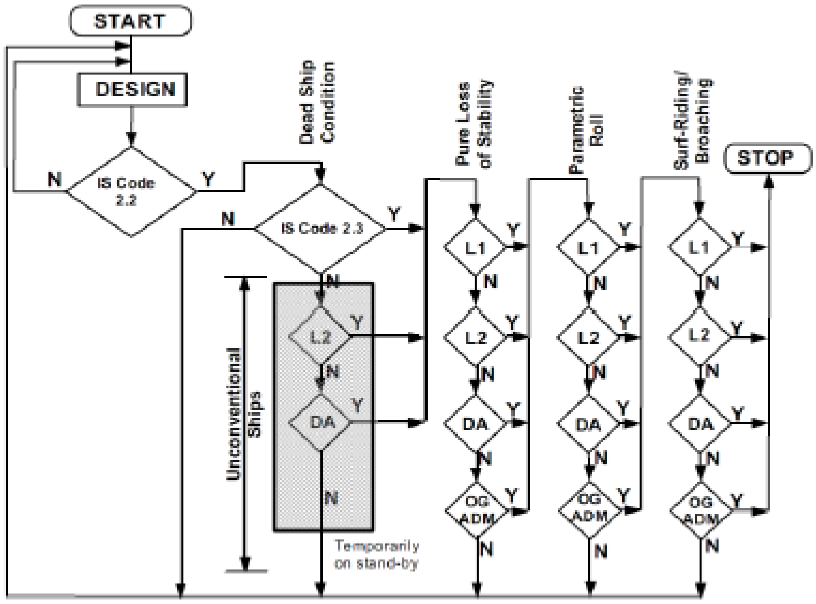


Figure 1: Multi-Tiered Approach for the Second Generation Intact Stability Criteria [12]

In order to comply with the regulation, each vessel will have to successfully pass vulnerability checks on all 4 forms of failure. Those checks consist of three levels. Failure to pass a level 1 check will require a level 2 check as well. Failure to pass a level 2 check will require a direct stability assessment. After that, ships that are still considered vulnerable to a certain form of failure will have to contact administration and may also require changes in design.

<u>Level 1</u> checks require simple algebraic calculations in order to detect vulnerability. Results are highly conservative in an effort to ensure a ship’s safety in waves. In this way, vessels which are not prone to e.g. large restoring arm variations such as bulk carriers, will easily pass Level 1 checks and move on to the next criterion without being forced to implement more detailed calculations. All level 1 equations and methods are deterministic.

<u>Level 2</u> checks require more complex calculations which may involve numerical solution of non-linear ordinary differential equations. They are also risk-based due to the random nature of the sea waves. Results lead to an achieved risk level for a certain form of failure and are

compared to the regulation standard. They are less conservative than Level 1 checks but more time consuming. Current regulation drafts are developed only for levels 1 and 2.

Direct Stability Assessment will be the last resort for those ships that fail the past two checks. No formal draft has been proposed yet, but according to various thoughts and ideas, computational hydrodynamic simulations will be required based on computational fluid dynamics. The main issue that arises from those simulations is how validation will be achieved between various numerical codes and methods.

All levels are to be consistent with each other. For example, any ship that is not vulnerable to level 1 checks, should never be vulnerable to level 2 checks and so on.

CHAPTER IV

Pure Loss of Stability

IV.1 Physical Background

Sailing through waves with high amplitude may lead to dramatic changes to a ship's waterplane area. Figures 2 and 3 show a container ship on a wave crest and trough respectively.

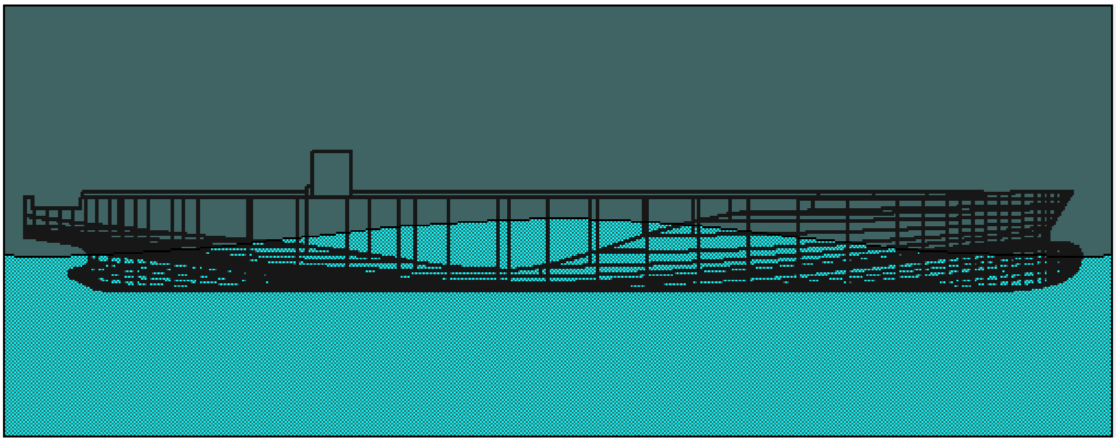


Figure 2: Container ship on a wave crest

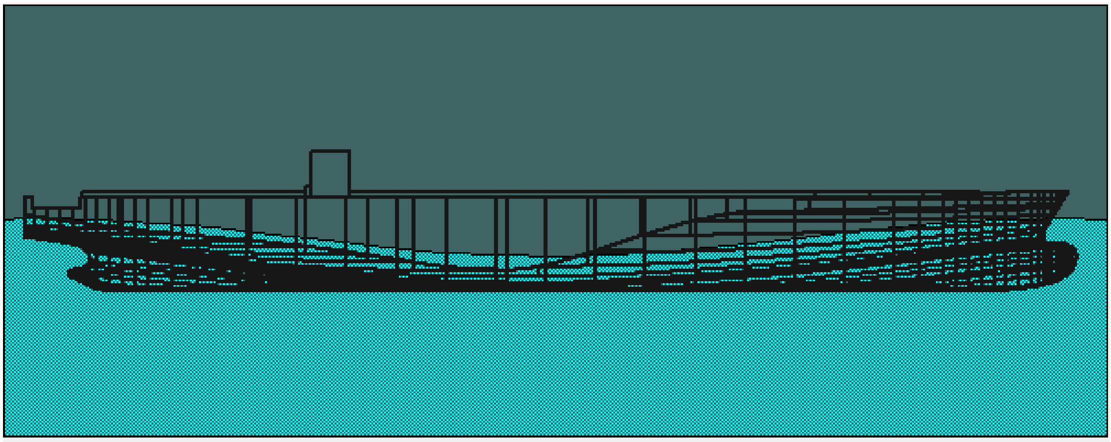


Figure 3: Container ship on a wave trough

While the ship is on the wave trough, draft at aft and fore sections is greater than in calm water. At the same time, draft at mid ship is reduced. This leads to an increase of waterplane area at aft and fore sections and a decrease at mid sections. When the ship is on the wave crest the situation is exactly the opposite; waterplane areas at aft and fore sections are reduced and increased at mid sections.

Conventional ship designs include wall sided mid ship sections and fore and aft sections with wider upper parts (flare). As a result, changes of waterplane areas are greater at aft and fore sections and remain almost constant around the mid ship.

Considering the above, waterplane areas on wave crests are smaller than those in calm water and on wave troughs, as shown in Figure 4.

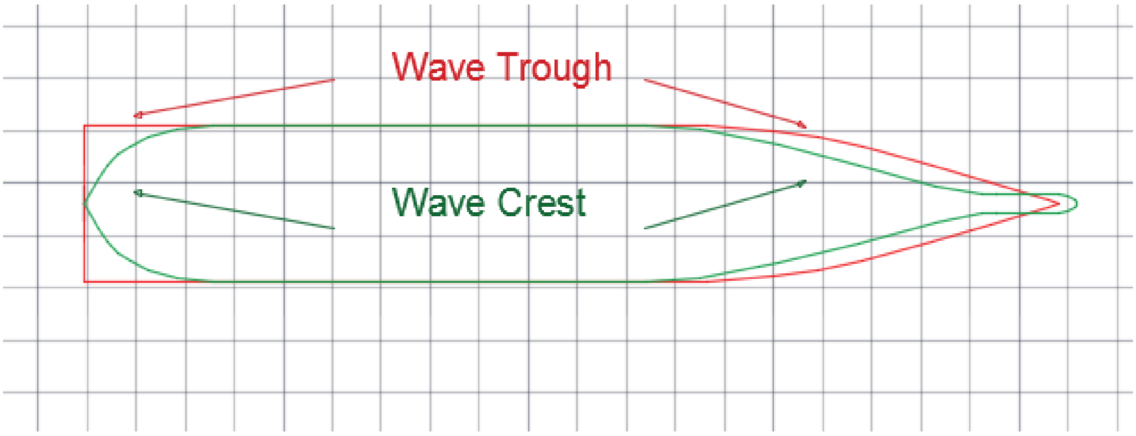


Figure 4: Waterplane areas on crest and trough

The value of initial metacentric height is given by:

$$GM = KB + BM - KG \qquad \textbf{[IV.1]}$$

The value of KG remains constant at all times for a specific loading condition. The value of KB is slightly increased when the ship is on a crest and slightly decreased when it remains on a trough, as is apparent from Figures 2 and 3.

The value of BM is given by:

$$BM = \frac{I}{\nabla} \qquad \textbf{[IV.2]}$$

Where ∇ is the volume of displacement and I is the transverse second moment of waterplane area given by:

$$I = \iint_{Awl} y^2 dxdy \qquad \textbf{[IV.3]}$$

Low values of waterplane area A_{wl} may lead to low values of BM and consequently, low or negative values of GM.

Pure Loss of Stability is the phenomenon, during which, the value of initial metacentric height GM is negative due to small waterplane areas that may occur while the ship sails through a wave crest. It may lead to capsizing if the amount of time spent with a negative GM is large enough to cause extreme heeling. The critical situation occurs when the vessel's speed is close to the wave's phase speed since under those circumstances the ship remains on a crest for a prolonged period of time.

The nature of this phenomenon is solely hydrostatic and thus, large roll damping is incapable of averting its consequences. The safest way to prevent its occurrence is by reducing the flare of fore and aft sections in an effort to moderate the dramatic changes of the waterplane area under the effect of waves.

IV.2 Draft Regulation

The regulation, as stated in Annex 18 of [13], is to be applied to all ships of length equal to 24 meters or greater for service speeds that lead to Froude numbers of 0.24 or greater. The following paragraphs contain draft regulations extracted from Annex 18 of [13].

IV.2.1 Level 1 Vulnerability Criteria

For every loading condition, level 1 vulnerability check is passed if:

$$GM_{\min} > R_{PLA} \qquad \textbf{[IV.4]}$$

Where R_{PLA} = 0.05 m and:

GM_{min} is the minimum value of the metacentric height at zero trim with taking consideration of free surface effects as a longitudinal wave passes the ship (m) which can be calculated as:

a) The minimum value calculated for the ship with free surface correction, corresponding to the loading condition under consideration, considering the ship to be balanced in sinkage and trim on waves with the following characteristics:

Wave length λ = L

Wave height $h = L \cdot S_W$ where S_W = 0.0334

and the wave crest centred at the longitudinal centre of gravity and at 0.1L, 0.2L, 0.3L, 0.4L, and 0.5L forward and 0.1L, 0.2L, 0.3L, and 0.4L aft thereof.

Or

b) $GM_{\min} = KB + \frac{I_L}{V} - KG$ (m) only if $\frac{V_D - V}{A_W(D-d)} \geq 1.0$ **[IV.5]**

Where:

d is draft amidships corresponding to the loading condition under consideration (m)

I_L is the moment of inertia of the waterplane at the draft d_L and at zero trim (m)

$d_L = d - \delta d_L$ (m)

KB is the height of the vertical centre of buoyancy corresponding to the loading condition under consideration (m)

KG is the height of the vertical centre of gravity corresponding to the loading condition under consideration (m)

V is the volume of displacement corresponding to the loading condition under consideration (m^3)

δd_L = $Min(d - 0.25 d_{full}, \frac{L \cdot S_W}{2})$ (m), and $d - 0.25 d_{full}$

S_W = 0.0334

D is the moulded depth at side to the weather deck (m)

V_D is the volume of displacement at waterline equal to D (m^3)

A_W is the waterplane area at the draft equal to d (m^2).

The method described above can be applied for non-even keel conditions.

If

$$\frac{V_D - V}{A_W (D - d)} < 1.0 \qquad \textbf{[IV.6]}$$

IV.2.2 Level 2 Vulnerability Criteria

A ship is considered not to be vulnerable to the pure loss of stability failure mode if the largest value among CR_1, CR_2, and CR_3, calculated according to the following paragraphs under the service speed, is less than the criterion standard R_{PL0} where:

$$R_{PL0} = 0.06 \text{ in case of Option A}$$
$$\phantom{R_{PL0} = } 0.15 \text{ in case of Option B}$$

Each of the three criteria, CR_1, CR_2, and CR_3, represents 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 1 for Option A or Table 2 for Option B.

Where,

$$CR_1 = \sum_{i=1}^{N} W_i C1_i = Weighted\ criterion\ 1$$
$$CR_2 = \sum_{i=1}^{N} W_i C2_i = Weighted\ criterion\ 2$$
$$CR_3 = \sum_{i=1}^{N} W_i C3_i = Weighted\ criterion\ 3$$

W_i is the weighting factor obtained from Table 1 for Option A or Table 2 for Option B

N is the total number of wave cases for which $C1_i$, $C2_i$, $C3_i$ are evaluated

$C1_i$, $C2_i$, $C3_i$ are the values of Criterion 1, Criterion 2 and Criterion 3 respectively evaluated according to next paragraphs.

Option A

Case number	Weight W_i	Wave length λ_i [m]	Wave height H_i [m]	Wave steepness $s_{w,i}$	$1/s_{w,i}$
1	0.000013	22.574	0.700	0.0310	32.2
2	0.001654	37.316	0.990	0.0265	37.7
3	0.020912	55.743	1.715	0.0308	32.5
4	0.092799	77.857	2.589	0.0333	30.1
5	0.199218	103.655	3.464	0.0334	29.9
6	0.248788	133.139	4.410	0.0331	30.2
7	0.208699	166.309	5.393	0.0324	30.8
8	0.128984	203.164	6.351	0.0313	32.0
9	0.062446	243.705	7.250	0.0297	33.6
10	0.024790	287.931	8.080	0.0281	35.6
11	0.008367	335.843	8.841	0.0263	38.0
12	0.002473	387.440	9.539	0.0246	40.6
13	0.000658	442.723	10.194	0.0230	43.4
14	0.000158	501.691	10.739	0.0214	46.7
15	0.000034	564.345	11.241	0.0199	50.2
16	0.000007	630.684	11.900	0.0189	53.0

Table 1: Wave characteristics for Option A

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

Length $\lambda = L$

Height $H_i = 0.01 \cdot iL, \quad \mathrm{i} = 1,2,...,10$

Specified wave cases for evaluation of the requirements are presented in Table 2. For use in Option B, N is to taken as 272. For each combination of H_s and T_z, W_i is obtained as the value in Table 2 divided by 100000, which is associated with a H_i calculated below and λ_i is taken as equal to L. Then the indices for each H_i, should be interpolated from the relationship between h and the indexes obtained above.

<u>Option B</u>

	Tz (s) = average zero up-crossing wave period															
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
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
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
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
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
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
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
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
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
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
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
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	0.0
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	0.0
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
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
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
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
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

Table 2: Wave characteristics for Option B

Criterion 1

Criterion 1 is provided in the following formula:

$$C1_i = \begin{cases} 1 & \phi_V < R_{PL1} = 30^o \\ 0 & otherwise \end{cases} \qquad \textbf{[IV.7]}$$

The angle of vanishing stability, φ_v, with free surface correction, 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 1 for Option A or Table 2 for Option B and with the wave crest centred at the longitudinal centre of gravity and at 0.1L, 0.2L, 0.3L, 0.4L, and 0.5L forward and 0.1L, 0.2L, 0.3L, and 0.4L aft thereof..

Criterion 2

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

$$C2_i = \begin{cases} 1 & \phi_s > R_{PL2a} = 15^o \text{ or } \phi_{loll} > R_{PL2b} = 25^o \\ 0 & otherwise \end{cases} \qquad \textbf{[IV.8]}$$

The angle of stable heel under action of heeling lever specified by R_{PL3}, φ_s, with free surface correction, in case of positive GM at the upright condition, 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 1 for Option A or Table 2 for Option B and with the wave crest centred at the longitudinal centre of gravity and at 0.1L, 0.2L, 0.3L, 0.4L, and 0.5L forward and 0.1L, 0.2L, 0.3L, and 0.4L aft thereof. The angle φ_{loll} is a maximum loll angle determined from the righting lever curve calculated for the ship, with free surface correction, 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 1 for Option A or Table 2 for Option B and with the wave crest centred at the longitudinal centre of gravity and at 0.1L, 0.2L, 0.3L, 0.4L, and 0.5L forward and 0.1L, 0.2L, 0.3L, and 0.4L aft thereof.

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:

$$C3_i = \begin{cases} 1 & GZ_{\max}(m) < R_{PL3} \\ 0 & otherwise \end{cases} \quad \textbf{[IV.9]}$$

Where $R_{PL3} = 8(H_i/\lambda)dF_N^2$.

GZ_{max} is determined as the smallest of maxima of the righting lever curves calculated for the ship, with free surface correction, 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 1 for Option A or Table 2 for Option B and with the wave crest centred at the longitudinal centre of gravity and at 0.1L, 0.2L, 0.3L, 0.4L, and 0.5L forward and 0.1L, 0.2L, 0.3L, and 0.4L aft thereof.

Where,

d is the draft of the loading condition under consideration (m)

F_N is Froude number corresponding to design speed

IV.3 Application

Draft regulations of Level 1 and Level 2 vulnerability criteria for pure loss of stability failure are applied for a post-Panamax container ship with the following characteristics:

Length L_{BP} (m)	264.4
Beam (m)	40
Depth (m)	24.3
Mean Draught (m)	13.97
Block Coefficient	0.6
GM (m)	0.61
Design Speed (knots)	24
Length of waterline (m)	269
Froude Number	0.2402

Since the Froude number that corresponds to design speed is marginally greater than the critical value of 0.24, we should proceed with level 1 vulnerability check.

IV.3.1 Level 1 Vulnerability Check

The minimum value of GM on the span of a wave is calculated by using Maxsurf Stability software. The wave under investigation has the following characteristics:

Wave length λ = 264.4 m

Steepness S_W = 0.0334

Wave height h = 8.83 m

The acquired minimum values of GM is GM_{min} = - 1.027< 0.05. Therefore a level 2 vulnerability check is required.

IV.3.2 Level 2 Vulnerability Check

Level 2 vulnerability checks require calculation of the maximum value of GZ, of loll angles and of angle of vanishing stability on the span of a number of waves with different characteristics. According to Option A the characteristics of those waves are shown in Table 3.

Case number	Weight	Wave length	Wave height	Wave steepness	
N	W_i	λ_i	H_i	$s_{w,i}$	$1/s_{w,i}$
1	0.000013	22.574	0.7	0.031	32.2
2	0.001654	37.316	0.99	0.0265	37.7
3	0.020912	55.743	1.715	0.0308	32.5
4	0.092799	77.857	2.589	0.0333	30.1
5	0.199218	103.655	3.464	0.0334	29.9
6	0.248788	133.139	4.41	0.0331	30.2
7	0.208699	166.309	5.393	0.0324	30.8
8	0.128984	203.164	6.351	0.0313	32
9	0.062446	243.705	7.25	0.0297	33.6
10	0.02479	287.931	8.08	0.0281	35.6
11	0.008367	335.843	8.841	0.0263	38
12	0.002473	387.44	9.539	0.0246	40.6
13	0.000658	442.723	10.194	0.023	43.4
14	0.000158	501.691	10.739	0.0214	46.7
15	0.000034	564.345	11.241	0.0199	50.2
16	0.000007	630.684	11.9	0.0189	53

Table 3: Characteristics of waves for Option A

All required parameters are calculated by using Maxsurf Stability software [18]. The results for each case are shown in Table 4.

N	φ_v(deg)	φ_{loll}(deg)	$GZ_{MAX,MIN}$(m)
1	46.4	0	0.629
2	46.4	0	0.624
3	46.1	0	0.602
4	45.8	0	0.575
5	44.9	0	0.493
6	45.6	0	0.465
7	40.8	21.5	0.143
8	0	-	0
9	0	-	0
10	0	-	0
11	0	-	0
12	37.1	25.6	0.063
13	39.5	22.4	0.14
14	41.2	20.8	0.208
15	42.5	18	0.289
16	43	14.7	0.324

Table 4: Results for the investigated ship for Option A

Cases 8, 9, 10 and 11 correspond to hydrostatic capsize where the GZ curve is like shown in Figure 5.

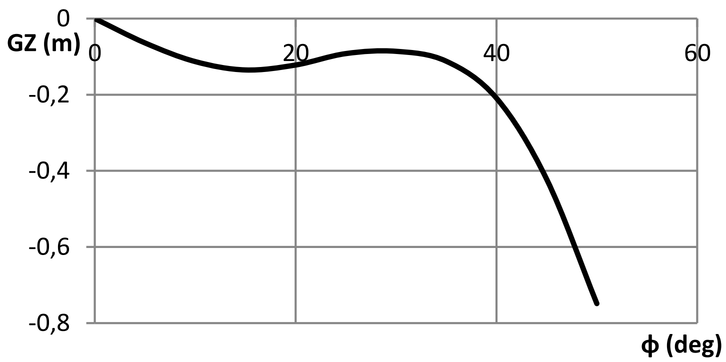


Figure 5: GZ curve on a wave where hydrostatic capsize occurs

For Option B the investigated waves have the characteristics shown in Table 5.

Case number	Weight	Wave length	Wave height	Wave steepness	$1/s_{w,i}$
N	W_i	λ_i [m]	H_i [m]	$s_{w,i}$	
1	0.000013	264.4	2.644	0.01	100
2	0.001654	264.4	5.288	0.02	50
3	0.020912	264.4	7.932	0.03	33.33333
4	0.092799	264.4	10.576	0.04	25
5	0.199218	264.4	13.22	0.05	20
6	0.248788	264.4	15.864	0.06	16.66667
7	0.208699	264.4	18.508	0.07	14.28571
8	0.128984	264.4	21.152	0.08	12.5
9	0.062446	264.4	23.796	0.09	11.11111
10	0.02479	264.4	26.44	0.1	10

Table 5: Characteristics of waves for Option B

The values of wave weight are calculated by linear interpolation between specific values of Table 2 as requested by the criterion. Those waves lead to the parameters shown in Table 6.

N	**φ_v(deg)**	**φ_{loll}(deg)**	**$GZ_{MAX,MIN}$(m)**
1	44.1	9.6	0.393
2	39.6	23.7	0.137
3	0	-	0
4	0	-	0
5	0	-	0
6	0	-	0
7	0	-	0
8	0	-	0
9	0	-	0
10	0	-	0

Table 6: Results for the investigated ship for Option B

and the values of the indices for both options are shown in Table 7.

Option A				Option B			
N	**C1i**	**C2i**	**C3i**	**N**	**C1i**	**C2i**	**C3i**
1	0	0	0	1	0	0	0
2	0	0	0	2	0	0	0
3	0	0	0	3	1	1	1
4	0	0	0	4	1	1	1
5	0	0	0	5	1	1	1
6	0	0	0	6	1	1	1
7	0	0	1	7	1	1	1
8	1	1	1	8	1	1	1
9	1	1	1	9	1	1	1
10	1	1	1	10	1	1	1
11	1	1	1				
12	0	1	1				
13	0	0	1				
14	0	0	0				
15	0	0	0				
16	0	0	0				

Table 7: Index values for both options

Finally the total values of the indexes for both options are:

$$CR_A = 0.4364 > 0.06 \qquad CR_B = 0.0234 < 0.15$$

IV.4 Evaluation

Pure loss of stability is a failure of hydrostatic nature which, also, depends on the amount of time spent on a wave with negative metacentric height. This amount of time is one of the most critical parameters of the problem but it is completely absent from the various calculations required by the criterion. Instead, only the critical Froude number is used as a dynamic parameter of the problem.

The critical value of Froude number is not a parameter of physical importance though; it represents the value of Froude number under which, no accidents related to pure loss of stability have ever been observed. In our case a design speed of 24 knots makes the criterion barely applicable to our ship. However, if the speed and thus, the value of Froude number are slightly reduced our ship will not have to comply with the regulation and will be considered not vulnerable to pure loss of stability. The validity of this aspect is at least questionable.

Another important issue that arises is the inconsistency between the two different methods suggested for the calculation of the index values. In our example of application, option A detects vulnerability to pure loss of stability while option B does not. Option B uses waves where their height is a percentage of the ship's length. For large ships, like post-Panamax container ships, those waves are rather high and their probabilities of occurring are close to zero. For our case the values of W_i are shown in Table 8.

N	W_i
1	0.23136
2	0.093799
3	0.0203423
4	0.00272549
5	0.00029068
6	0.000010164
7	0
8	0
9	0
10	0

Table 8: Probabilities of the investigated waves

Out of the ten investigated waves, only 6 have non-zero probabilities. This makes Option B less credible for large ships where high values of length between perpendiculars lead to improbable waves.

To sum up, draft regulation for pure loss of stability failure requires some further development before it evaluates a ship's vulnerability adequately. The current state of the criterion suffers from the issues mentioned earlier which could be partially fixed by keeping Option A instead of B and introducing the parameter of time under negative metacentric height. According to [20] "time-below critical GM" can be modelled as:

$$tbc = \frac{x2 - x1}{|c - V_s|} \qquad \textbf{[IV.10]}$$

Where *x1, x2* are the longitudinal positions on the wave between which *GM* has negative values, c is wave celerity and V_s is the design speed. Then the criterion values for each wave case could be:

$$Cr1_i = \frac{m \cdot tbc_i}{T_0} \qquad \textbf{[IV.11]}$$

Where *m* is the displacement and T_0 the natural roll frequency. This method, while not very complex, uses a simple model that combines the dynamic and hydrostatic nature of the problem which could lead to more credible results.

CHAPTER V

Parametric Rolling

V.1 Physical background

Parametric rolling is a form of instability in waves that leads to large roll angles despite the lack of transverse wave excitation. It occurs when the restoring moment is time dependent under the effect of longitudinal waves. Fast ships with fine hulls and flare in aft and fore sections are considered prone to parametric rolling. While loss of life or capsize is highly improbable for large vessels, loss of containers is a common issue [5]. A confirmed parametric rolling accident is APL China's in 1998 [19]. The outcome is shown in Figure 6. Parametric rolling may also prove hazardous for other types of ships, such as cruise vessels [17].

Figure 6: APL China after extreme parametric rolling in rough seas [34]

The mathematical model presented is based on the works of [1] and [33].

The linear equation of uncoupled roll motion under longitudinal waves without wave excitation is:

$$I_{XX}\ddot{\varphi} + \mathrm{B}\dot{\varphi} + mgGM(t) = 0 \qquad \textbf{[V.1]}$$

As we've seen in Chapter IV.1, longitudinal waves may cause changes in the values of A_{wl}, BM and GM. We can assume that under harmonic waves the variation of GM will also become harmonic in the linear problem. As a result, the restoring moment is:

$$mgGM(t) = mg[GM_0 + \Delta GM\cos(\omega_e t)] \qquad \textbf{[V.2]}$$

Where GM_0 is the initial metacentric height in calm water and ΔGM is the amplitude of the harmonic variation of GM, as shown in Figure 5.

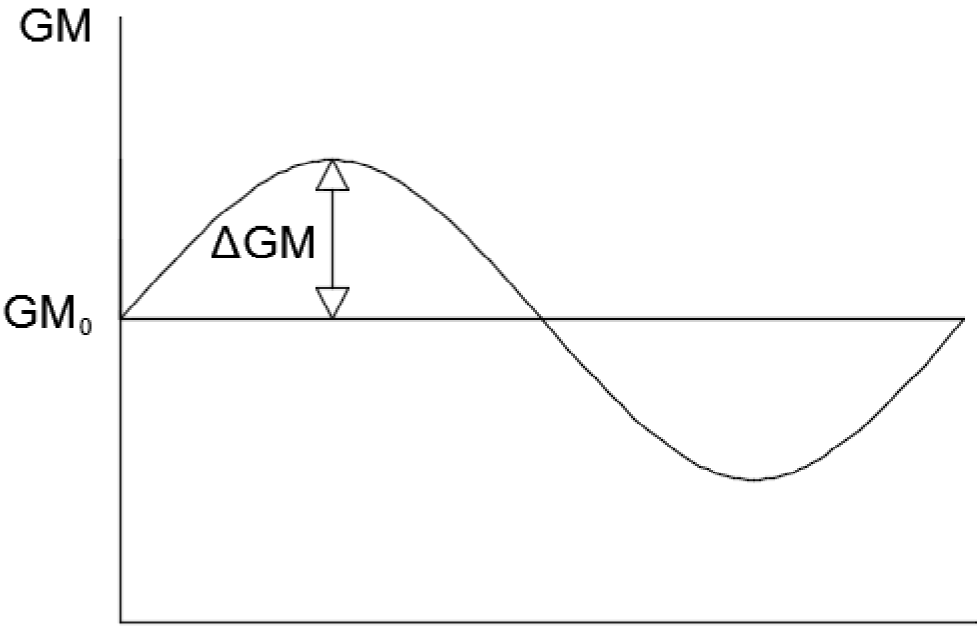


Figure 5: Time-dependent GM variation

Then the uncoupled roll equation is:

$$I_{XX}\ddot{\varphi} + \mathrm{B}\dot{\varphi} + mg([GM_0 + \Delta GM\cos(\omega_e t)] = 0 \quad \textbf{[V.3]}$$

Or:

$$\ddot{\varphi} + b\dot{\varphi} + \omega_0^2[1 + h\cos(\omega_e t)]\varphi = 0 \quad \textbf{[V.4]}$$

Where $h = \dfrac{\Delta GM}{GM_0}$. By neglecting the damping term b we acquire **Mathieu's** equation:

$$\ddot{\varphi} + \omega_0^2[1 + h\cos(\omega_e t)]\varphi = 0 \quad \textbf{[V.5]}$$

Mathieu's equation can be solved analytically, approximately by using the "harmonic balance" method [33]. Then we receive the boundary:

$$h = 2\left|1 - \frac{\omega_e^2}{\omega_0^2}\right| \quad \textbf{[V.6]}$$

When $h > 2\left|1-\frac{\omega_e^2}{\omega_0^2}\right|$ the solution of Mathieu's equation leads to unbounded parametric resonance, while $h < 2\left|1-\frac{\omega_e^2}{\omega_0^2}\right|$ leads to steady rolling with amplitude equal to initial angle, as shown in Figure 6.

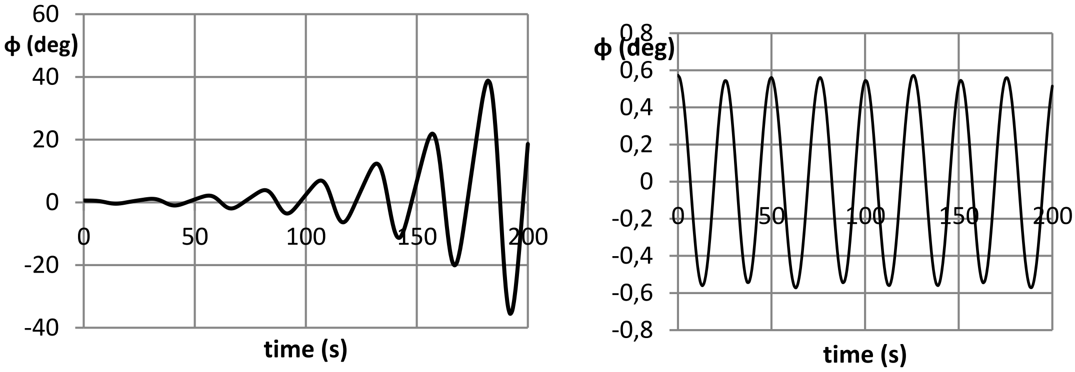


Figure 6: Parametric resonance and steady rolling based on Mathieu's equation

The boundary of h that we receive by this approach corresponds to the first boundary between stable and unstable oscillations called "Principal Resonance". Numerical solution of Mathieu's equation for multiple pairs of $(h, \frac{\omega_0^2}{\omega_e^2})$ gives the Ince-Strutt diagram shown in Figure 7.

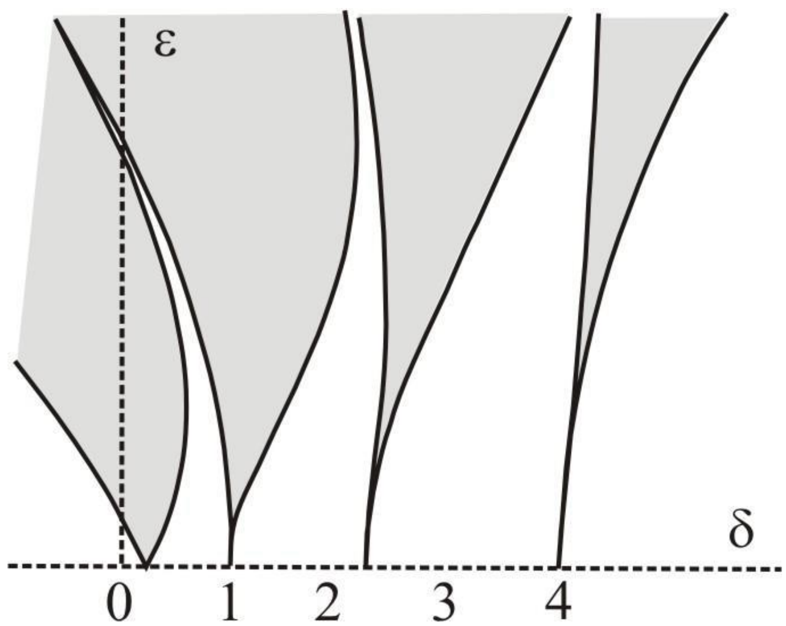


Figure 7: Ince-Strutt diagram [33]

Where $\delta = \dfrac{\omega_0^2}{\omega_e^2}$, $\varepsilon = h\dfrac{\omega_0^2}{\omega_e^2}$, U corresponds to unstable solutions and S to stable. When $\dfrac{4\omega_0^2}{\omega_e^2} \approx n^2$, where *n* any integer, unstable solutions occur for any h. These points correspond to parametric resonance. For $n = 1$ resonance is called "Principal", as mentioned before. For $n = 2$ "Fundamental Resonance" occurs.

Mathieu's equation does not include a damping term. However, damping in the uncoupled roll equation plays a significant role in reducing the consequences of parametric rolling, even for small values of damping. In Figure 8 the effect of damping in the principal boundary of Ince-Strutt diagram is shown.

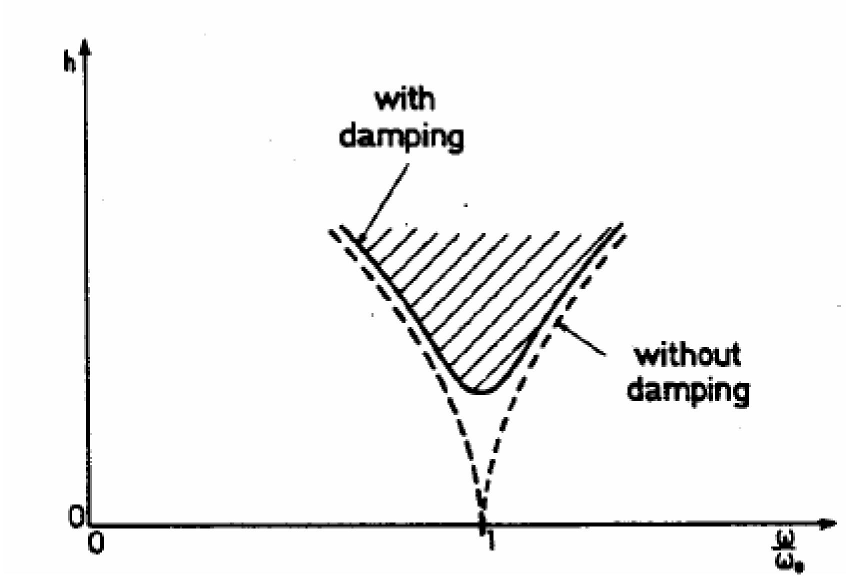


Figure 8: Effect of damping [33]

The unstable regions of Ince-Strutt diagram are shifted upwards which means that for low values of h, parametric rolling will never occur. As a result, ships with full lines and small changes to waterplane areas and thus, low values of h, are safe from this form of instability. At the same time, roll damping reduces the area of the parametric rolling region. Roll damping may be increased by using bilge keels or anti-roll tanks [29].

Mathieu's linear equation is capable of detecting parametric rolling. However, roll response is unbounded and continues growing to infinity, as shown in Figure 7. In order to receive a bounded response an equation with non-linear restoring terms is required, e.g. in the following form:

$$(\mathrm{I}_{xx} + \delta I_{xx})\ddot{\varphi} + B_{44}\dot{\varphi} + mgGZ \qquad \textbf{[V.7]}$$

Where GZ is modelled as:

$$GZ = GM\varphi + c_3\varphi^3 + c_5\varphi^5 + GM_{amp}\cos(\omega_e t)\varphi \qquad \textbf{[V.8]}$$

Where c_3, c_5 are restoring coefficients and GM_{amp} is GM variation in waves. Then, roll response is bounded as shown in Figure 7.

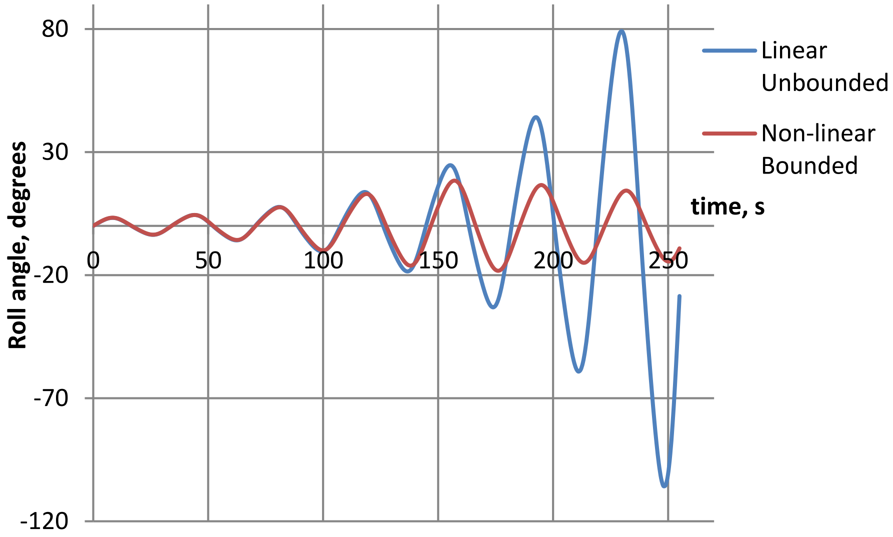


Figure 7: Roll response for linear (bounded) and non-linear (unbounded) equations

Consequently, a non-linear roll equation should be solved when the amplitude of parametric rolling is to be determined.

V.2 Draft Regulation

In this chapter, draft regulation of parametric rolling stability failure is presented, in accordance with Annex 16 of [13].

This regulation is to be applied to all ships of length equal to 24 meters or greater. The following paragraphs contain draft regulations extracted from Annex 16 of [13].

V.2.1 Level 1 Vulnerability Criteria

For every loading condition, level 1 vulnerability check is passed if:

$$\frac{\Delta GM}{GM} \leq R_{PR} \quad \textbf{[V.9]}$$

Where R_{PR} is the criterion standard given by:

R_{PR} = 1.87, if the ship has a sharp bilge;

$$R_{PR} = 0.17 + 0.425\left(\frac{100A_k}{LB}\right), \text{ if } \quad C_m > 0.96; \quad \textbf{[V.10]}$$

R_{PR} = $0.17 + (10.625 \times C_m - 9.775)\left(\frac{100A_k}{LB}\right)$, if $0.94 < \mathrm{C_m} < 0.96$;

R_{PR} = $0.17 + 0.2125\left(\frac{100A_k}{LB}\right)$, if $\mathrm{C_m} < 0.94$; *and*

$\left(\frac{100A_k}{LB}\right)$ should not exceed 4;

Where:

- A_k is bilge keel area (m^2)
- Cm is the midship coefficient
- L is length between perpendiculars (m)
- B is the ship's breadth (m)
- GM is the initial metacentric height in calm water including free surface correction for the loading condition under investigation (m)
- ΔGM is the amplitude of metacentric height variation which can be calculated by two different ways (m):

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

Where:

- V is the displacement volume of the loading condition under investigation (m^3)
- V_D is the displacement volume of the loading condition that corresponds to draft equal to depth (m^3)
- A_W is waterplane area of the loading condition under investigation (m^2)
- D is the ship's depth (m)
- d is the draught of the loading condition under investigation (m)
- I_H, I_L are the second moments of waterplane area at drafts d_H and d_L respectively where:
- δd_H = $Min(D - d, \frac{L \cdot S_W}{2})$ (m)
- δd_L = $Min(d - 0.25d_{full}, \frac{L \cdot S_W}{2})$ (m), and $d - 0.25d_{full}$ should not be taken less than zero
- d_H = $d + \delta d_H$ (m)
- d_L = $d - \delta d_L$ (m)
- d_{full} = draft corresponding to the fully loaded departure condition (m)
- S_W = 0.0167, wave steepness

b) ΔGM may be regarded as half the difference between the maximum and minimum value of initial metacentric height GM including free surface correction, on the span of a wave with the following characteristics:

Wave Length $\lambda = L$

Wave Height $h = L \cdot S_W$, where S_W = 0.0167 is wave steepness

V.2.2 Level 2A Vulnerability Criteria

For every loading condition, level 2A vulnerability check is passed if:

$$C1 = \sum_{i=1}^{N} W_i C_i \le R_{PR0} \qquad \textbf{[V.10]}$$

Where

- N is number of investigated waves
- W_i is the probability of a wave λ_i, H_i
- C_i = 0, if the requirements for either the GM variation in waves or the ship speed in waves is satisfied

  = 1, if not
- $C1$ is level 2B vulnerability index
- R_{PR0} is the criterion standard, as defined in Level 1

The requirement for the variation of GM in waves is satisfied if, for each wave specified in Table 9:

$$GM(H_i, \lambda_i) > 0 \quad and \quad \frac{\Delta GM(H_i, \lambda_i)}{GM(H_i, \lambda_i)} < R_{PR} \qquad \textbf{[V.11]}$$

Where,

- $R_{PR} = 0.06$ is the criterion standard
- $\Delta GM(H_i, \lambda_i)$ is one-half the difference between the maximum and minimum values of the metacentric height calculated for the ship (m), 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_i and a λ_i

- $GM(H_i, \lambda_i)$ is the average value of the metacentric height calculated for the ship (m) including free surface correction, 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_i and a λ_i
- H_i is a wave height specified in Table 9 (m)
- λ_i is a wave length specified in Table 9 (m)

The requirement for the ship speed in waves is satisfied if, for a wave specified in Table 9:

$$V_{PR\,i} > V_s \qquad \textbf{[V.12]}$$

Where,

- V_S is the service speed (m/s)
- V_{PRi} is the reference ship speed (m/s) corresponding to principal parametric resonance conditions, when $GM(H_i, \lambda_i)>0$:

$$V_{PRi} = \left| \frac{2\lambda_i}{T_\phi} \cdot \sqrt{\frac{GM(H_i, \lambda_i)}{GM}} - \sqrt{g\frac{\lambda_i}{2\pi}} \right| \qquad \textbf{[V.13]}$$

- T_φ is the roll natural period in calm water (s)
- GM is the metacentric height in calm water (m) including free surface correction
- $GM(H_i, \lambda_i)$ is is the average value of the metacentric height calculated for the ship (m) including free surface correction, 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_i and a λ_i (m)
- λ_i is a wave length specified in Table (m)
- g is gravitational acceleration of 9.81 m/s^2
- | | is the absolute value operator.

The specified wave cases for evaluation of the requirements are presented in Table 9.

Wave case number	Weight W_i	Wave length λ_i (m)	Wave height H_i (m)
1	0.000013	22.574	0.350
2	0.001654	37.316	0.495
3	0.020912	55.743	0.857
4	0.092799	77.857	1.295
5	0.199218	103.655	1.732
6	0.248788	133.139	2.205
7	0.208699	166.309	2.697
8	0.128984	203.164	3.176
9	0.062446	243.705	3.625
10	0.024790	287.931	4.040
11	0.008367	335.843	4.421
12	0.002473	387.440	4.769
13	0.000658	442.723	5.097
14	0.000158	501.691	5.370
15	0.000034	564.345	5.621
16	0.000007	630.684	5.950

Table 9: Wave cases for level 2A parametric rolling evaluation

V.2.3 Level 2B Vulnerability Criteria

For every loading condition, level 2B vulnerability check is passed if:

$$C2 \leq 0.15 \quad \textbf{[V.14]}$$

The value of *C2* is calculated as an average of values of C2(Fn_i,β_i), each of which is a weighted average from the set of waves specified in Table 11, for each set of Froude numbers and wave directions specified:

$$C2 = \left[\sum_{i=1}^{3} C2(Fn_i, \beta_h) + C2(0, \beta_h) + \sum_{i=1}^{3} C2(Fn_i, \beta_f)\right] / 7 \qquad \textbf{[V.15]}$$

Where,

- C2(Fn_i,β_h) is calculated as specified in the next paragraph with the ship proceeding in head waves with a speed equal to V_i
- C2(Fn_i,β_f) is calculated as specified in the next paragraph with the ship proceeding in following waves with a speed equal to V_i
- Fn_i is the Froude number corresponding to speed V_i
- V = V_s K_i, means the ship speed (m/s) for each corresponding encounter
- V_S is ship service speed (m/s)
- g is the gravitational acceleration of 9.81 m/s^2
- K_i is the encounter speed factor as obtained from Table 10.

i	K_i	Corresponds to encounter with:
1	1.0	Head or following waves at V_s
2	0.866	Waves with 30° relative bearing to ship centreline at V_s
3	0.50	Waves with 60° relative bearing to ship centreline at V_s

Table 10: Corresponding encounter speed factor

The value of C2(Fn,β) is calculated as a weighted average from the set of waves specified in Table 11 for a given Froude number Fn and a wave direction β.

$$C2(Fn, \beta) = \sum_{i=1}^{N} W_i C_i \qquad \textbf{[V.16]}$$

Where,

- W_i the weighting factor for the respective wave cases specified in Table 11
- C_i = 1, if the maximum roll angle evaluated according to next paragraph exceeds 25 degrees
- = 0, otherwise
- N is the total number of wave cases for which the maximum roll angle is evaluated for a combination of speed and ship heading

The maximum roll amplitude in head and following waves is evaluated as recommended in the next paragraph for each speed, V_i. For each evaluation, the calculation of stability in waves should assume the ship to be balanced in sinkage and trim on a series of waves with the following characteristics:

Wave length, $\lambda = L$;

Wave height, $h_j = 0.01 \cdot jL$, where $j = 1,2,...,10$.

The evaluation of the maximum roll amplitude should be calculated using an equation of uncoupled roll motion, in which the following components 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
- variation of stability in waves on the roll restoring moment.

The evaluation of roll amplitude should be carried out using a verifiable method.

In the absence of roll decay test data, roll damping may be modelled using either a simplified Ikeda's method or type-specific empirical data (with bilge keels geometry effect included), if appropriate. The forward speed effect may be taken into account for the lift component using Ikeda’s or an equivalent method.

For each wave case with λ_i, H_i,, W_i is obtained from Table 11 or a similar table of wave data satisfactory to the Administration. Each cell of the Table corresponds to an average zero up-crossing wave period, *Tz*, and a significant wave height, H_s and is associated with a representative wave height, *Hr*, using a procedure. The maximum roll amplitude, corresponding to the representative wave height, *Hr*, is obtained by linear interpolation of the maximum roll amplitudes for wave heights, h_j.

	Tz (s) = average zero up-crossing wave period															
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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

Table 11: Wave case occurrences per 100,000 observation for roll response evaluation in parametric rolling

V.3 Application

Draft regulations of Level 1 and Level 2 vulnerability criteria for parametric rolling failure are applied for a baby post-Panamax container ship with the following characteristics:

Length L_{BP} (m)	238.38
Beam (m)	37.3
Depth (m)	19.6
Mean Draught (m)	11.52
Block Coefficient	0.657
GM (m)	0.84
Design Speed (knots)	21
Length of waterline (m)	249.85
Froude Number	0.218
Midship coefficient C_M	0.981
Bilge keel area (m^2)	59.34

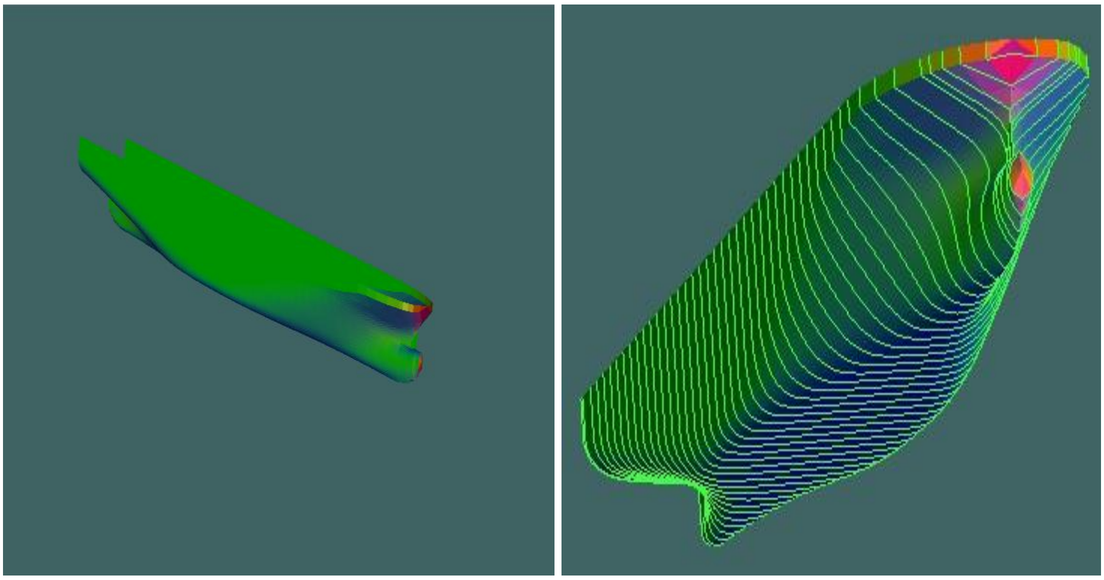


Figure 8: Maxsurf model of investigated container ship [3]

V.3.1 Level 1 Vulnerability Check

According to level 1 vulnerability criteria for parametric rolling the ratio $\Delta GM / GM$ is to be compared to the value of the standard R_{PR} . For our ship ΔGM is calculated as half the difference between the minimum and maximum values of *GM* on the span of a wave with the following characteristics:

$$\lambda = 238.35m$$

$$H = 3.98m$$

By using Maxsurf stability software, we calculate values of *GM* considering the ship to be balanced on ten different points along the wave. Then the value of *GM* variation is:

$$\Delta GM = 1.905$$

and the ratio:

$$\Delta GM / GM = 2.268$$

Alternatively, since $\frac{V_D - V}{A_W (D-d)} = 1.03 \geq 1.0$ ΔGM may be calculated by:

$$\Delta GM = \frac{I_H - I_L}{2V} = 1.537$$

And the GM ratio is

$$\Delta GM / GM = 1.83$$

The value of the standard R_{PR} given by V.10 is:

$$R_{PR} = 0.454$$

The effect of midship coefficient C_M and bilge keel area A_k to the value of R_{PR} are shown in Figures 9 and 10.

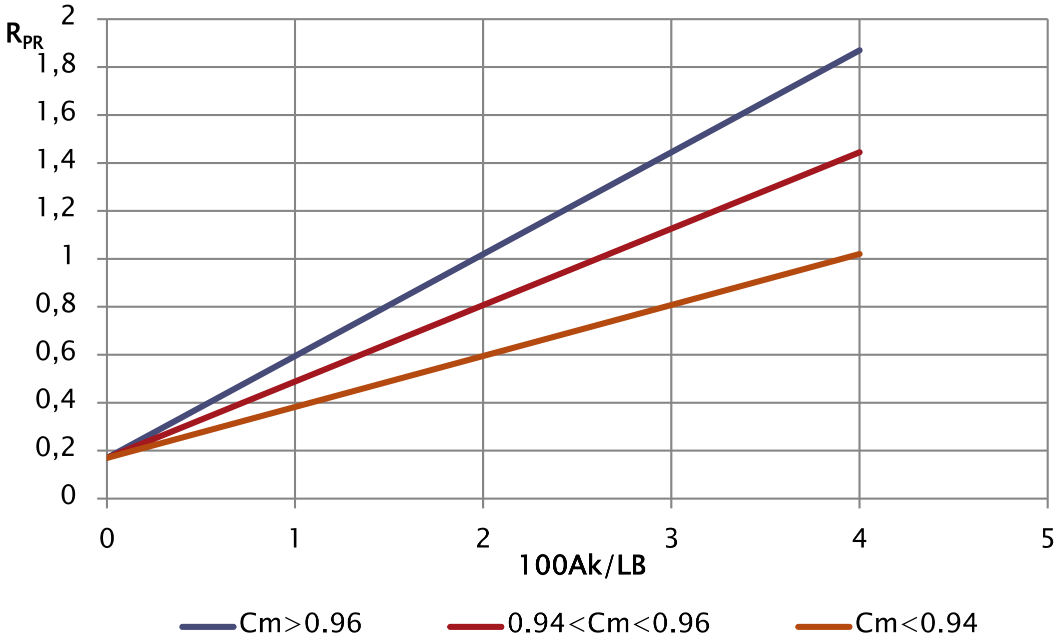


Figure 9: Effect of bilge keel area to R_{PR}

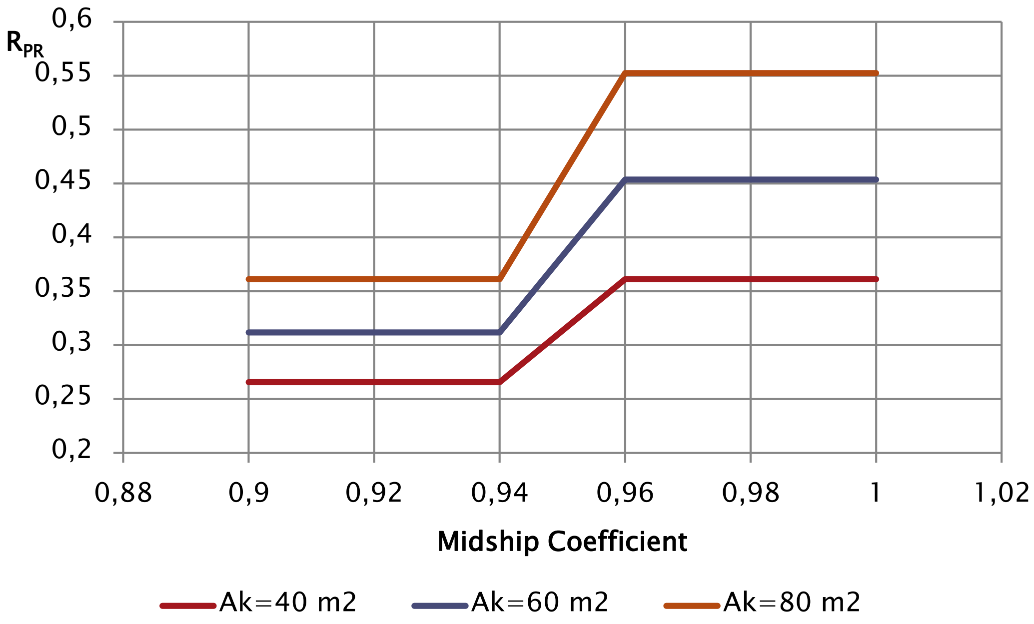


Figure 10: Effect of midship coefficient to R_{PR}

Since $\Delta GM / GM > R_{PR}$ for both methods level 1vulnerability is detected. We should then proceed with level 2 vulnerability check.

V.3.2 Level 2 Vulnerability Check

Level 2A parametric roll vulnerability check requires the calculation of the ratio $\Delta GM / GM$ for 16 different waves with the characteristics shown in Table 12:

Wave case	Weight	Wave length	Wave height
N	W_i	λ_i (m)	H_i (m)
1	0.000013	22.574	0.35
2	0.001654	37.316	0.495
3	0.020912	55.743	0.857
4	0.092799	77.857	1.295
5	0.199218	103.655	1.732
6	0.248788	133.139	2.205
7	0.208699	166.309	2.697
8	0.128984	203.164	3.176
9	0.062446	243.705	3.625

Wave case	Weight	Wave length	Wave height
N	W_i	λ_i (m)	H_i (m)
12	0.002473	387.44	4.769
13	0.000658	442.723	5.097
14	0.000158	501.691	5.37
15	0.000034	564.345	5.621
16	0.000007	630.684	5.95

Table 12: Characteristics of investigated waves

Moreover, the design speed is to be compared to the reference speed that corresponds to Mathieu resonance for each wave. The results are shown in Table 13:

Number of case	GM ratio	GM ratio standard	Design speed	Reference speed	Index
N	$\Delta GM/GM$	R_{PR}	V_s (kn)	V_{pr} (kn)	C_i
1	0.019649	0.312	21	9.315865	0
2	0.041761	0.312	21	11.15934	0
3	0.115511	0.312	21	12.63027	0
4	0.217327	0.312	21	13.71858	0
5	0.305677	0.312	21	14.36822	0
6	0.340246	0.312	21	14.66149	1
7	0.768832	0.312	21	14.59313	1
8	0.945338	0.312	21	13.94147	1
9	0.955487	0.312	21	12.78883	1
10	0.904534	0.312	21	11.43227	1
11	0.826754	0.312	21	9.876	1
12	0.746459	0.312	21	8.106557	1
13	0.667079	0.312	21	6.020765	1
14	0.587566	0.312	21	3.594552	1
15	0.515518	0.312	21	1.156107	1
16	0.453507	0.312	21	1.941388	1

Table 13: Results for Level 2A vulnerability check

The total value of C_1 index for level 2A vulnerability is:

$$C_1 = 0.6854 > 0.06 = R_{PR0}$$

That means that level 2A vulnerability is detected. We should then proceed to a level 2B vulnerability check.

Level 2B requires calculation of parametric roll amplitude for ten different waves and seven different wave directions (0^o, 30^o, 60^o, 120^o, 150^o, 180^o and 180^o with zero speed). The waves have the characteristics shown in Table 14.

Case number	Weight	Wave length	Wave height	Wave steepness	$1/s_{w,i}$
N	W_i	λ_i [m]	H_i [m]	$s_{w,i}$	
1	0.236665	238.35	2.3835	0.01	100
2	0.119647	238.35	4.767	0.02	50
3	0.033621	238.35	7.1505	0.03	33.33333
4	0.006146	238.35	9.534	0.04	25
5	0.000933	238.35	11.9175	0.05	20
6	0.000102	238.35	14.301	0.06	16.66667
7	0	238.35	16.6845	0.07	14.28571
8	0	238.35	19.068	0.08	12.5
9	0	238.35	21.4515	0.09	11.11111
10	0	238.35	23.835	0.1	10

Table 14: Wave characteristics for level 2B check

Calculation of parametric roll amplitude is carried out by using 3 different methods. The first method is a numerical solution of a non-linear equation formulated in [13]:

$$I_{xx}\ddot{\varphi} + B_{44}\dot{\varphi} + mgGZ = 0 \qquad \textbf{[V.17]}$$

Where I_{xx} is the roll moment of inertia, B_{44} is the linear damping coefficient and GZ is the restoring arm which is modelled as:

$$GZ = GM_0\varphi + l_3\varphi^3 + l_5\varphi^5 + GZ_W \qquad \textbf{[V.18]}$$

Where GM_0 is the initial metacentric height in calm water, l_3,l_5 are third and fifth order restoring coefficients and GZ_W is the restoring arm in waves which is modeled as:

$$GZ_W = GM_{mean}\varphi + GM_{amp}\cos\omega_e t\left\{1 - \left(\frac{\varphi}{\pi}\right)^2\right\}\varphi \qquad \textbf{[V.19]}$$

Where GM_{mean} is the mean of GM variation in waves, GM_{amp} is the amplitude of GM variation in waves and ω_e is the encounter frequency.

Parametric roll amplitude is also calculated by solving numerically the averaged equation of V.17, as it is formulated in [13]:

$$\left\{\frac{\pi^2\omega_e 8\alpha}{(2\pi^2 - A^2)\omega_0^2}\right\}^2 + \left\{\frac{6A^2\omega_0^2 - 8\pi^2\omega_0^2}{4(\pi^2 - A^2)\omega_0^2}\frac{GM_{mean}}{GM_0} + \frac{-5\pi^2 A^4 l_5\omega_0^2 - 6\pi^2 A^2 l_3\omega_0^2 + 8\pi^2\omega_e^2 - 8\pi^2\omega_0^2}{4(\pi^2 - A^2)\omega_0^2}\right\}^2 = \left(\frac{GM_{amp}}{GM_0}\right)^2 \qquad \textbf{[V.20]}$$

Where A is parametric roll amplitude, ω_0 is natural roll frequency and α is linear damping coefficient. An older example of the principles behind this method can be found in [6] and [30].

Last but not least, another non-linear parametric roll equation is solved numerically in order to calculate roll amplitude. This equation is formulated in [26] and [27]:

$$\ddot{\varphi} + 2\zeta\omega_0\dot{\varphi} + \omega_0^2[1 - h\cos(\omega_e t)]\varphi - c_3\omega_0^2\varphi^3 - c_5\omega_0^2\varphi^5 \qquad \textbf{[V.21]}$$

Where ζ is linear damping coefficient, $h = \frac{GM_{amp}}{GM_{mean}}$ and c_3,c_5 are restoring coefficients.

Each equation is solved numerically with an initial rolling angle of 0.01 rad. A time domain of 5000 seconds is used. Steady motion is considered to be achieved after 4000 seconds. A quantic fit approximation of GZ curve is used as shown in Figure 11.

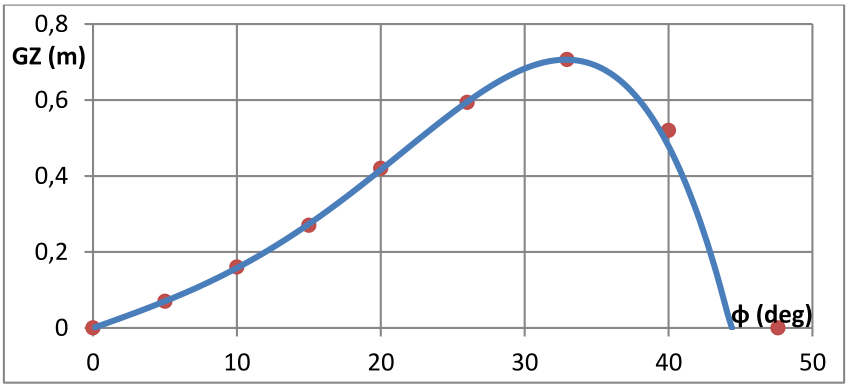


Figure 11: Quantic fit of GZ curve

It is important that the fifth order approximation fits closely the points of the restoring arm up to its maximum value. For greater angles, capsize is essentially inevitable and thus, fitting of the last two points is not necessary.

Natural roll period is calculated by using Kato's formula, as requested in [13]. According to Kato's formula, roll gyration can be calculated as:

$$\left(\frac{K}{B}\right)^2 = 0.125\left[C_u C_b 1.10 C_u(1 - C_b)\left(\frac{H_s}{d} - 2.20\right) + \left(\frac{H_s}{B}\right)^2\right] \qquad \textbf{[V.22]}$$

where K is roll gyration, B is moulded breadth, C_b is block coefficient, $C_u = A_u/(L_u B)$, A_u is projected area of upper deck where L_u is overall length deck of upper deck, d is design draft,

H_s is effective depth $H_s = D + \left(\frac{A'}{L_{pp}} \right)$ where D is depth, L_{pp} is length between perpendiculars, $A' = A + A_c$ where A' is lateral projected area of forecastle and deck house (A) and on deck cargoes (A_C). Roll moment of inertia can be calculated as:

$I_{xx} = \Delta K^2$ where Δ is the ship's displacement and K is roll gyration. The relation between roll moment of inertia and roll natural frequency is:

$$\omega_0 = \sqrt{\frac{mgGM}{Ixx}} \ , \ T_0 = 2\pi \sqrt{\frac{Ixx}{mgGM}}$$

For our ship $T_0 = 39.26s$

Damping coefficient was calculated by Ikeda's method, including bilge keel components, as suggested in [13].

The results of the indexes for each method can be seen in the next table.

Index	**Averaging**	**SDC**	**Spyrou**
C2	0.0239	0.000163	0.03457
RPR	0.15	0.15	0.15

Table 15: Index values for level 2B

Despite the large differences between each method, level 2B vulnerability is not detected.

V.4 Evaluation

V.4.1 Effect of ratio $\alpha = \frac{4\omega_0^2}{\omega_e^2}$

Application of level 2B vulnerability criteria requires parametric roll simulation under the effect of waves with length equal to ship length. This limits ratio $a = \frac{4\omega_0^2}{\omega_e^2}$ to a constant value. For following waves this value is $a = 2.04$. Ratio α has an important effect on the dynamic behavior of parametric rolling. In order to investigate this effect, a bifurcation diagram will be used as formulated by [26].

The amplitude of parametric rolling for a system with linear damping and 5th order restoring can be calculated by:

$$A^2 = -\frac{3c_3}{5c_5} \pm \sqrt{\left(\frac{3c_3}{5c_5}\right)^2 - \frac{8}{5c_5}\left(-1+\frac{1}{\alpha} \pm \sqrt{\frac{h^2}{4} - \frac{4k^2}{\omega_0^2 \alpha}}\right)} \qquad \textbf{[V.23]}$$

where A is roll amplitude, $c3,c5$ are 3[rd] and 5[th] order restoring coefficients, ω_0 is natural roll frequency, k is linear damping coefficient, $a = \frac{4\omega_0^2}{\omega_e^2}$ and $h = \frac{GM_{amp}}{GM_{mean}}$. The bifurcation diagrams that occur for various values of α are shown in Figures 12 to 19.

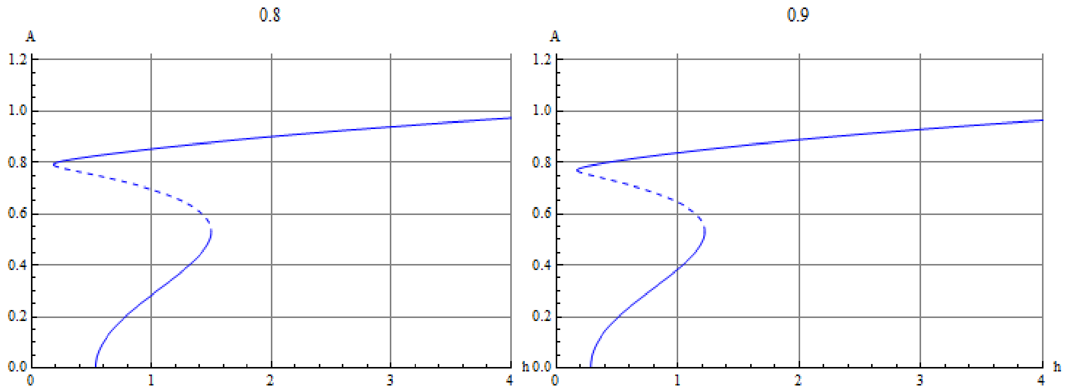


Figure 12: Bifurcation diagrams of parametric roll for α=0.8 and α=0.9

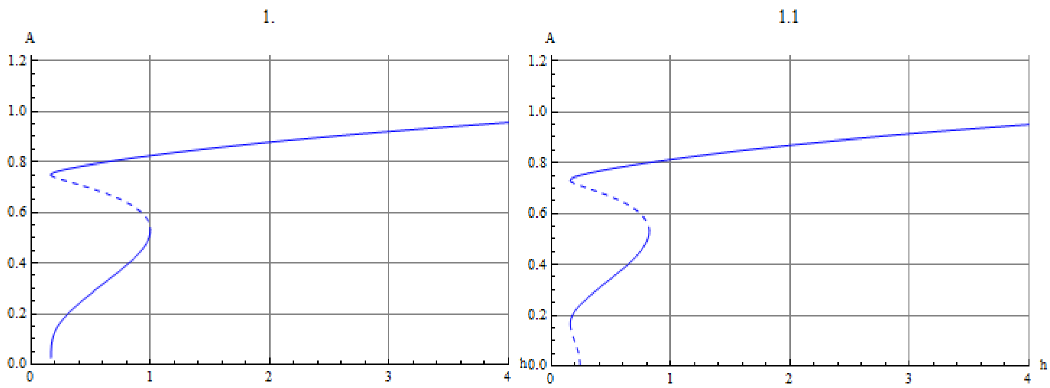


Figure 13: Bifurcation diagrams of parametric roll for α=1 and α=1.1

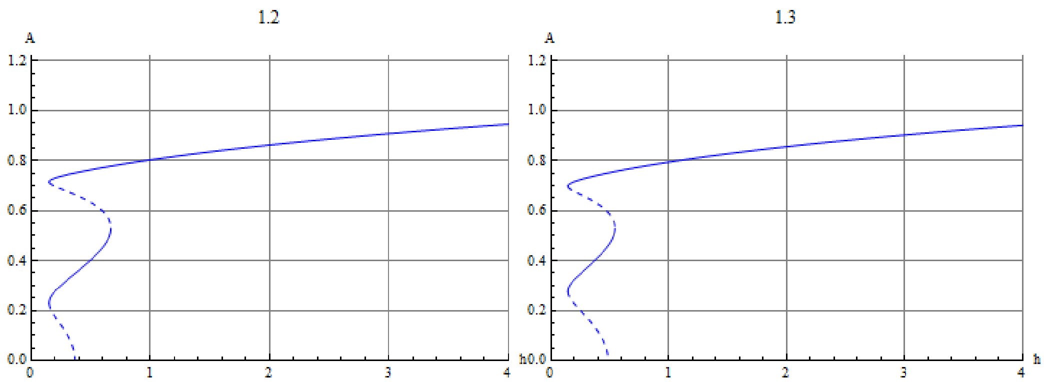


Figure 14: Bifurcation diagrams of parametric roll for α=1.2 and α=1.3

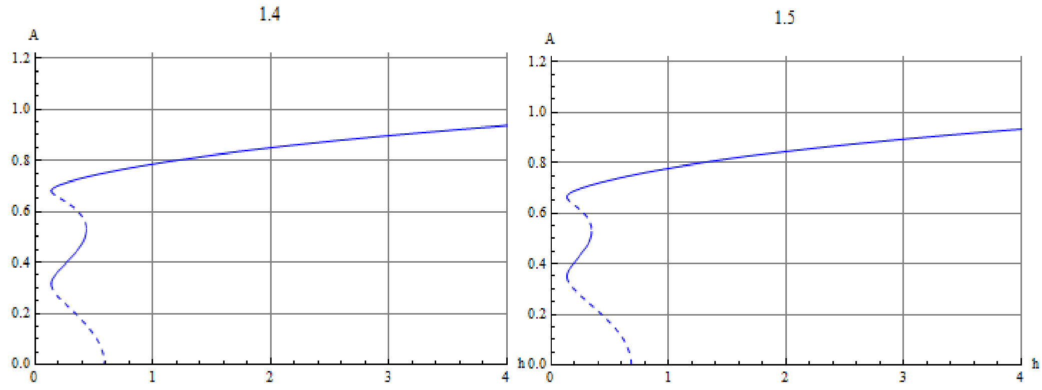


Figure 15: Bifurcation diagrams of parametric roll for α=1.4 and α=1.5

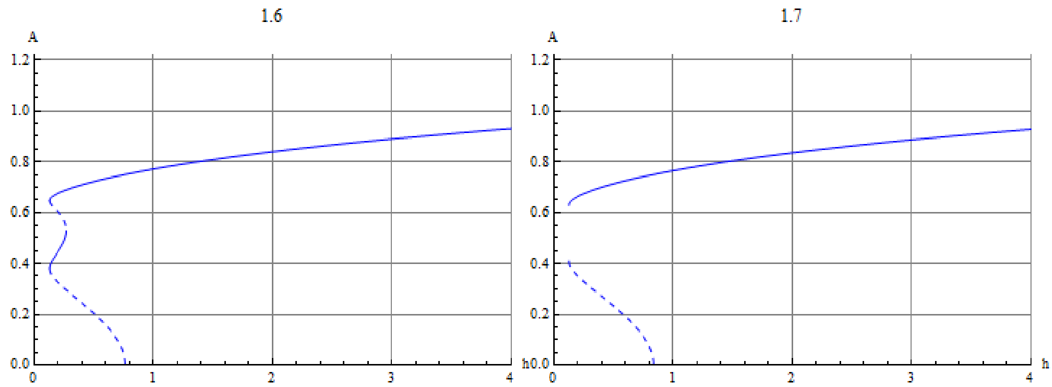


Figure 16: Bifurcation diagrams of parametric roll for α=1.6 and α=1.7

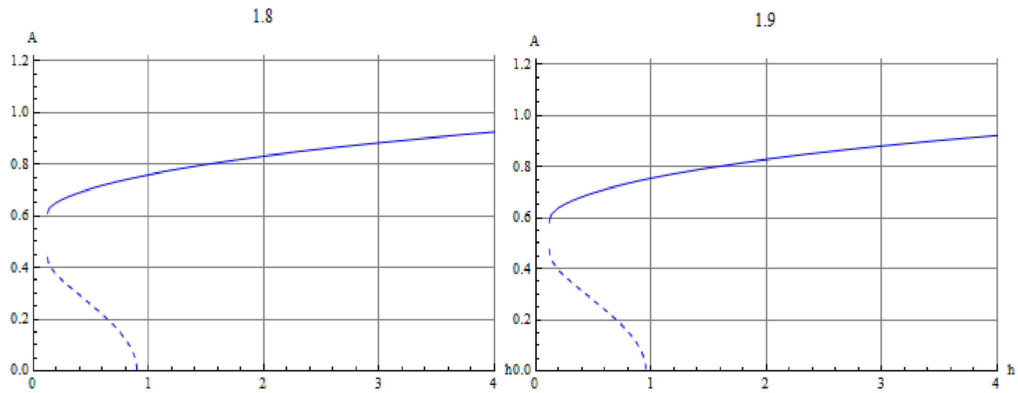


Figure 17: Bifurcation diagrams of parametric roll for α=1.8 and α=1.9

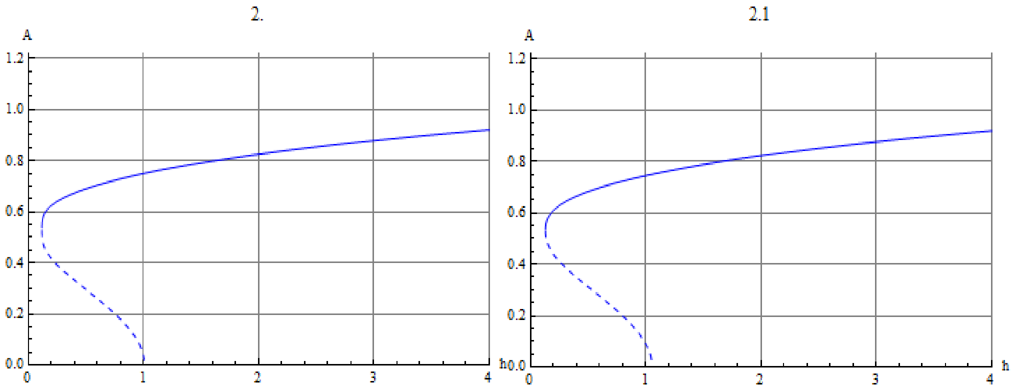


Figure 18: Bifurcation diagrams of parametric roll for α=2 and α=2.1

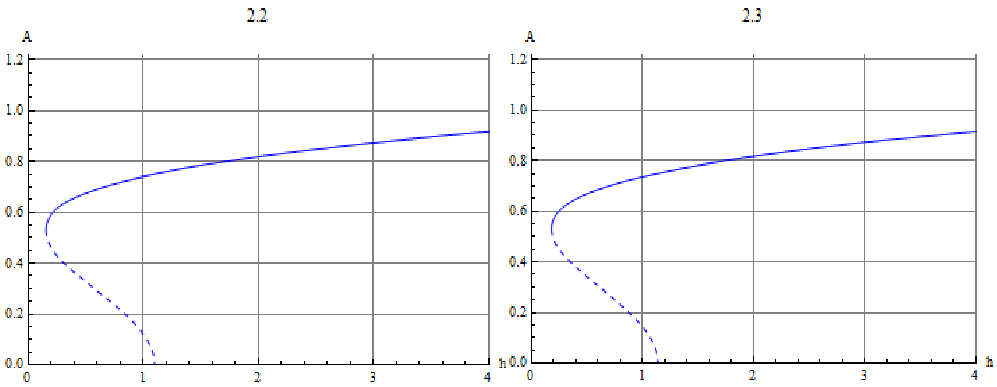


Figure 19: Bifurcation diagrams of parametric roll for α=2.2 and α=2.3

According to Figures 12 to 19, by modifying ratio α a different combination of stable and unstable solutions may coexist. From α=0.8 to α=1 solid lines represent two stable solutions and the dashed line one unstable solution. From α=1.1 to α=1.6 one more unstable solution appears. From a=1.7 to a=2.3 the central pair of stable and unstable lines vanishes and only a pair of stable and unstable regions exists.

Consequently, parameter α is crucial in determining the dynamic qualitative characteristics of the parametric roll response. By limiting the investigated wave height to λ=L only one value of α is investigated which depends on the ship's speed and natural roll frequency. In this way, more critical conditions that occur i.e. for α=1(principal resonance) are neglected. In our case, the most dangerous condition for low values of h, occurs for α=0.8 which leads to a stable steady amplitude of 0.8rad=45.8°. However, this condition is neglected since it would require a different encounter frequency in order to appear.

V.4.2 Effect of investigated waves to Level 2B index

Level 2B vulnerability check requires calculation of parametric roll amplitude under the effect of ten different waves with the characteristics shown in Table 16.

Case number	Weight	Wave length	Wave height	Wave steepness	$1/s_{w,i}$
N	W_i	λ_i [m]	H_i [m]	$s_{w,i}$	
1	0.236665	238.35	2.3835	0.01	100
2	0.119647	238.35	4.767	0.02	50
3	0.033621	238.35	7.1505	0.03	33.33333
4	0.006146	238.35	9.534	0.04	25
5	0.000933	238.35	11.9175	0.05	20
6	0.000102	238.35	14.301	0.06	16.66667
7	0	238.35	16.6845	0.07	14.28571
8	0	238.35	19.068	0.08	12.5
9	0	238.35	21.4515	0.09	11.11111
10	0	238.35	23.835	0.1	10

Table 16: Wave characteristics for level 2B check

It is obvious that out of the 10 cases only 6 have a non-zero probability. This tends to be the case for large vessels where the wave height is expressed as a percentage of the ship's length and leads to long waves that are extremely high. In this way, only small waves contribute to the weighted average of the index and thus, smaller values of C2 may occur.

In order to counter this issue, the 16 wave cases of Table 17 may be used.

Wave case	Weight	Wave length	Wave height
N	W_i	λ_i (m)	H_i (m)
1	0.000013	22.574	0.35
2	0.001654	37.316	0.495
3	0.020912	55.743	0.857
4	0.092799	77.857	1.295
5	0.199218	103.655	1.732
6	0.248788	133.139	2.205
7	0.208699	166.309	2.697
8	0.128984	203.164	3.176
9	0.062446	243.705	3.625
10	0.02479	287.931	4.04
11	0.008367	335.843	4.421
12	0.002473	387.44	4.769
13	0.000658	442.723	5.097
14	0.000158	501.691	5.37
15	0.000034	564.345	5.621
16	0.000007	630.684	5.95

Table 17: Alternative wave characteristics for level 2B check

Then we receive the following results for each method:

Index	Averaging	SDC	Spyrou
C2	0.224	0.0632	0.0623
RPR	0.15	0.15	0.15

Table 18: Index values for level 2B for 16 waves

By comparing Table 18 to Table 14 we may notice that the values of C2 indices are greater for all methods if we use 16 waves. Moreover, according to the averaging method level 2 vulnerability is detected. Considering the above, it may be wiser to apply the calculations for 16 random waves instead of limiting the wave length to λ=L.

V.4.3 Effect of method used to calculate parametric roll amplitude

Calculations of parametric roll amplitude carried out in V.4.2 and V.3 prove that there is an inconsistency between the three methods used. In order to detect the origins of those inconsistencies between the three index values, we should investigate the parametric roll amplitudes calculated by each method.

Results for following seas for the 10 wave cases of Table 16 are shown in Figure 20.

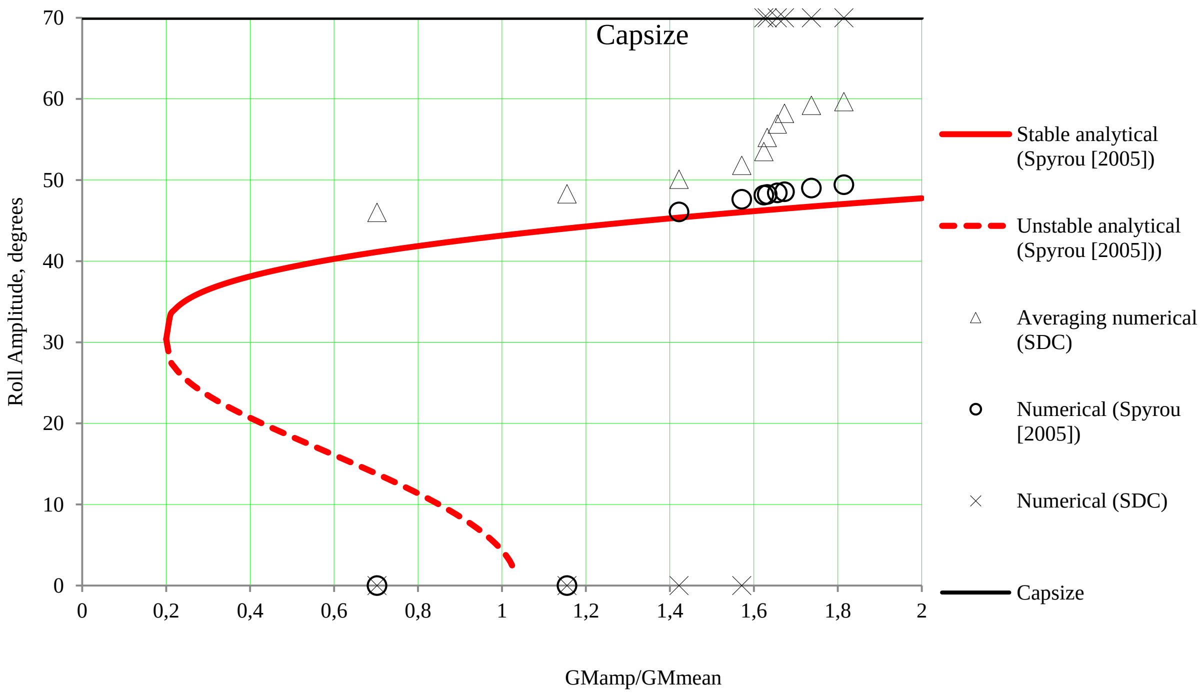
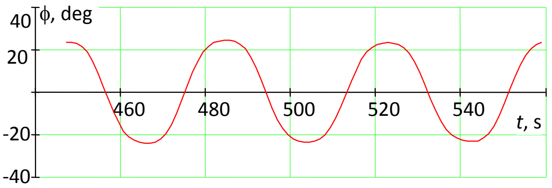


Figure 20: Parametric roll amplitude for 10 different waves [21]

According to Figure 20, calculated parametric roll amplitudes are close either to the red solid line of steady parametric resonance or to the x-axis which detects no parametric roll amplitude and corresponds to decaying rolling. Time-domain history of those two situations is shown in Figure 21.



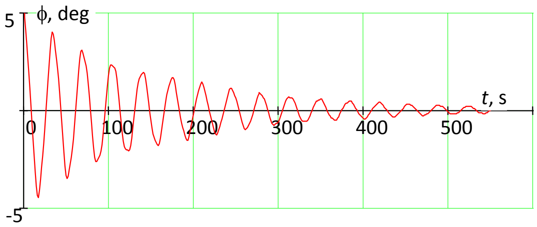


Figure 21: Time histories of steady parametric resonance and decaying rolling [21]

Numerical solution of SDC's equation may lead to roll responses that jump to infinity, as shown in Figure 22. This essentially means that capsize is detected.

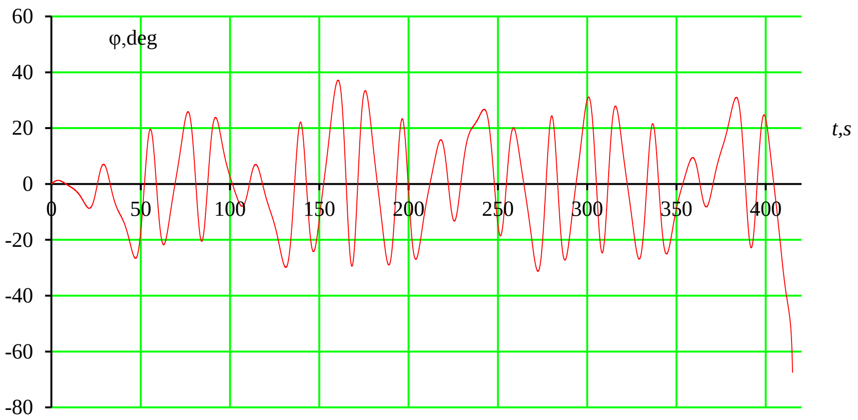


Figure 22: Time history of roll response for numerical solution of SDC's equation [21]

In Figure 20, a roll angle of 70 degrees is considered as a capsize limit and is represented by the solid black line.

It is easy to observe that the value of the parameter GM_{amp}/GM_{mean} after which parametric resonance is detected varies for each applied method. This inconsistency leads to different values of the criterion indices. In order to avoid this, clear guidance on the calculation of the required parameters and the methods used is necessary.

Another troubling aspect is that the parametric rolling equations presented earlier are to be applied for the calculation of roll amplitudes not only in head and following seas but also for heading angles of 30, 60, 120 and 150 degrees. For those angles, wave excitation exists since the integration of Froude-Krylov pressure around the wetted surface for waves that are not parallel to the roll axis of the ship, generate transverse forces as shown in Figure 23.

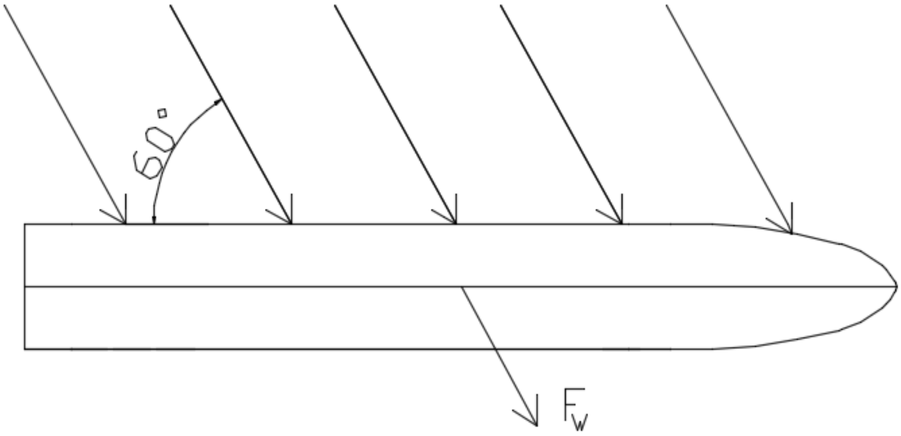


Figure 23: Wave excitation F_w for wave heading angle of 60 degrees

However, roll equations suggested by the regulation draft do not include wave excitation terms and thus, results for wave heading angles other than head and following seas are questionable.

V.4.3 Effect of initial conditions

Initial conditions may have an important impact on the calculation of parametric roll amplitude. According to Figure 20, for values of GM_{amp}/GM_{mean} between 0.2 and 1.05 where stable and unstable curves coexist, solutions may appear close to the stable or unstable curves. In Figure 24 the importance of the initial conditions is shown; for an initial roll angle of 35 degrees parametric rolling is detected for all 16 cases while for an initial roll angle of 0.6 degrees the ship is prone to parametric rolling only for 8 cases.

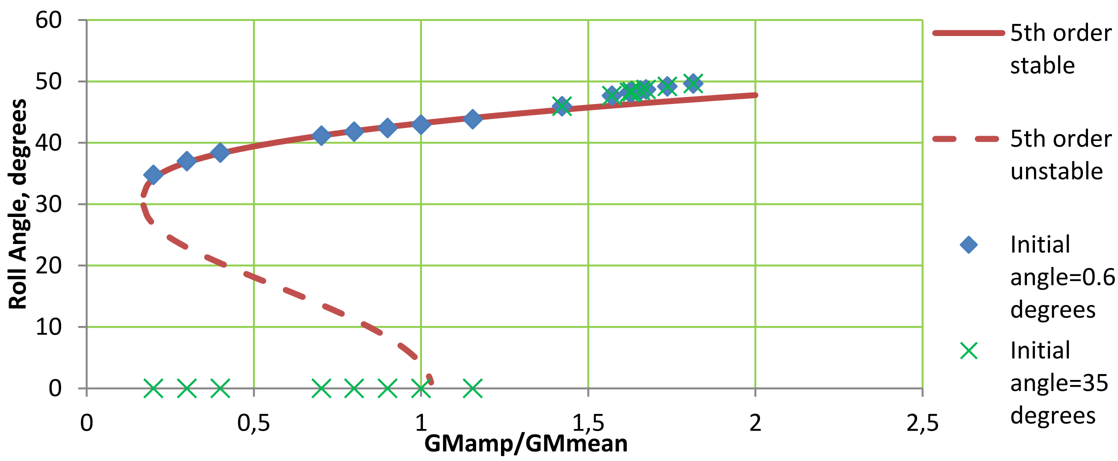


Figure 24: Effect of initial conditions to roll amplitude

V.4.4 Effect of non-linear damping

According to Annex 16 of [13], non-linear damping is to be calculated by a procedure shown in Appendix A. In order to determine its effect on parametric rolling amplitude, equation V.21 including non-linear damping *δ* is solved:

$$\ddot{\varphi}+2k\dot{\varphi}+\delta\dot{\varphi}^3+\omega_0^2[1-h\cos(\omega_e t)]\varphi-c_3\omega_0^2\varphi^3-c_5\omega_0^2\varphi^5 \qquad \textbf{[V.23]}$$

According to the structure of the corresponding solutions a) of the roll equation with quantic restoring with linear damping [26], b) of the roll equation with cubic restoring and cubic damping [26], it is conjectured that the steady amplitude of the roll equation V.23 obtains approximately the following form when the non-linear damping coefficient *δ* is included:

$$A^2=-\frac{3c_3}{5c_5}\pm\sqrt{\left(\frac{3c_3}{5c_5}\right)^2-\frac{8}{5c_5}\left(-1+\frac{1}{\alpha}\pm\sqrt{\frac{h^2}{4}-\left(\frac{2k}{\omega_0\sqrt{\alpha}}+\frac{3\delta\omega_0}{4\alpha^{1.5}}\right)^2}\right)} \qquad \textbf{[V.24]}$$

For our application, the procedure of Appendix A yields the following results:

Ikeda's dimensionless damping coefficients for roll angle of 1 and 20 degrees are respectively $\widehat{B}_{44,1}=0.00413$, $\widehat{B}_{44,20}=0.00938$, and by using Ikeda's normalising, $B_{44,1}=2.872\times10^8$, $B_{44,20}=6.528\times10^8$. Then, by utilizing A.5:

$$a=\frac{B_{44,1}}{2(I_{xx}+J_{xx})}\frac{\pi}{\omega_\phi}=0.127 \qquad a_e=\frac{B_{44,20}}{2(I_{xx}+J_{xx})}\frac{\pi}{\omega_\phi}=0.289$$

Then linear and 3rd order damping coefficients are:

$$\alpha=\frac{\omega_\phi}{\pi}a=0.00647 \qquad \gamma=\frac{4c}{3\pi^2}\left(\frac{2\pi}{\omega_\phi}\right)=4.0548$$

Where:

$$c=\frac{a_e-a}{\phi_m^2}=0.849$$

and φ_m is equal to 20 degrees. For V.23 and V.24 $\delta=\gamma=4.0548$.

Results for the 10 investigated wave cases for initial roll angle of 35 degrees are shown in Figures 25 to 30 for various values of non-linear damping.

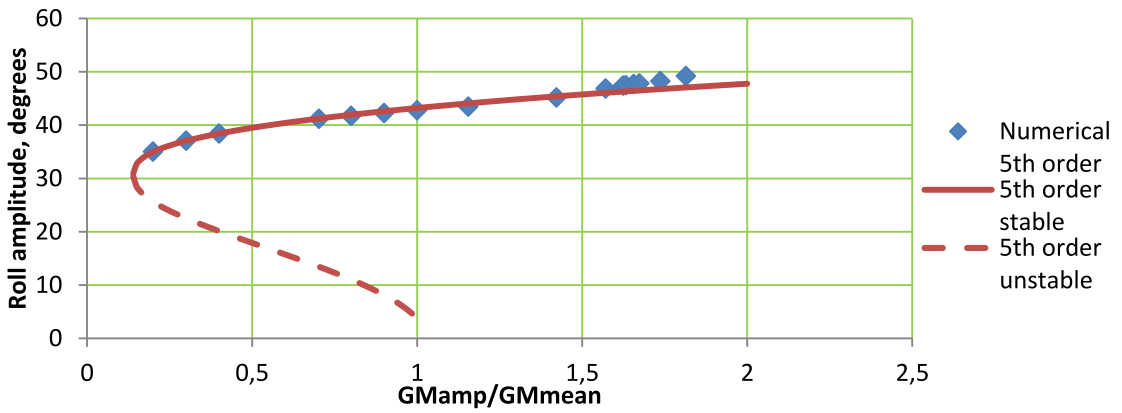


Figure 25: Roll amplitude for δ=0.045

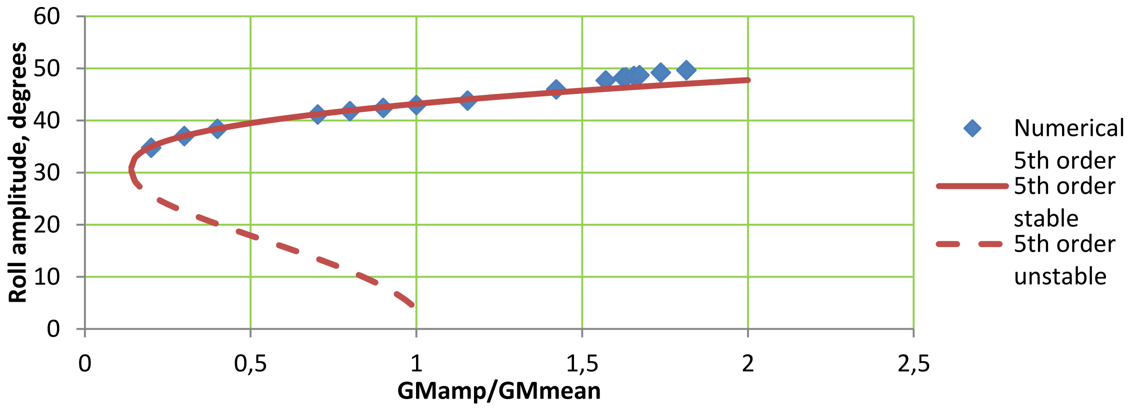


Figure 26: Roll a mplitude for δ=0.45

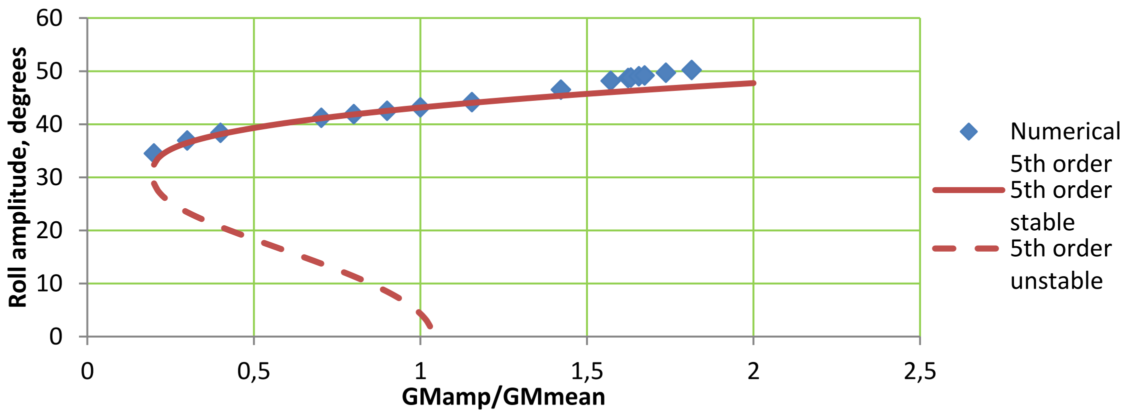


Figure 27: Roll amplitude for δ=0.8

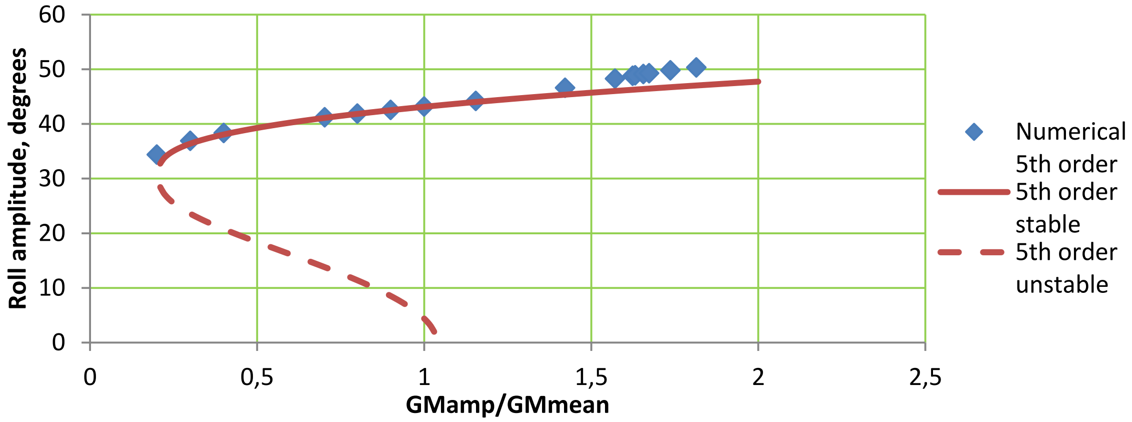


Figure 28: Roll amplitude for δ=0.9

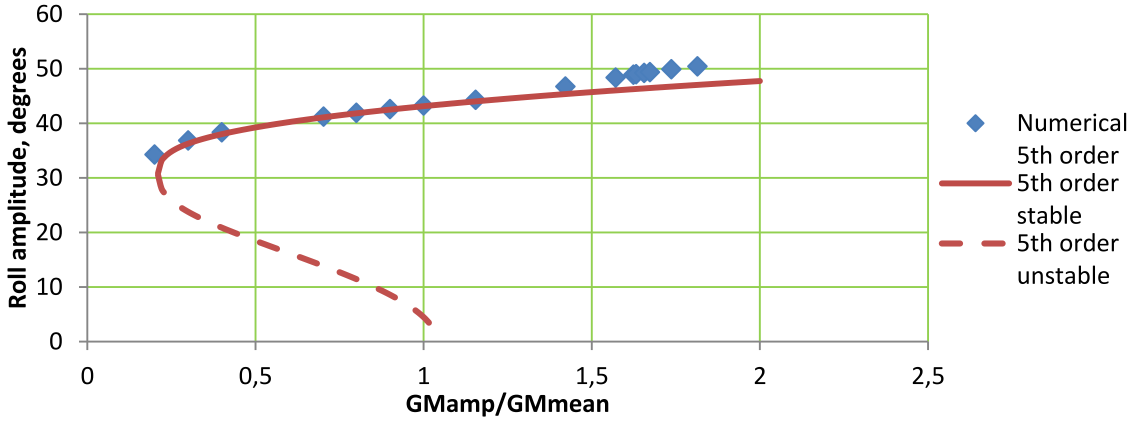


Figure 29: Roll amplitude for δ=1

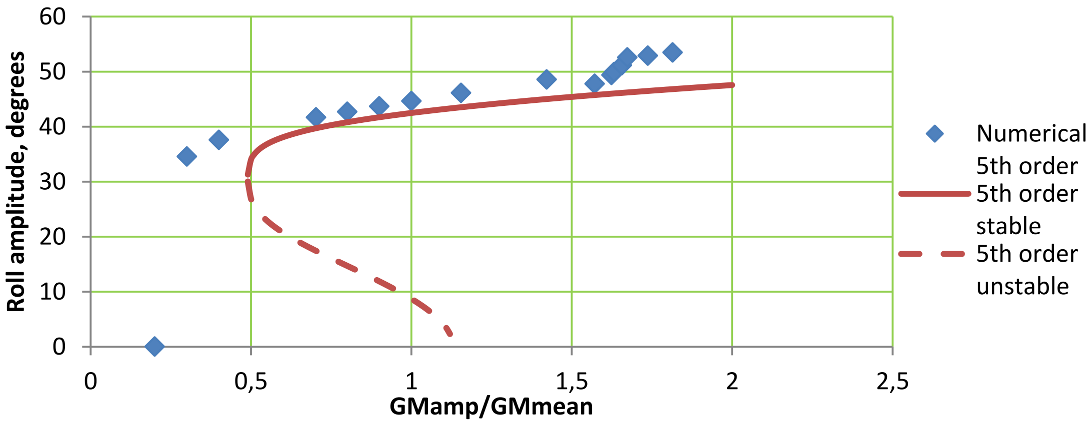


Figure 30: Roll amplitude for δ=4.5

Non-linear roll damping has a greater effect on roll amplitude for values greater than δ=1. However, value δ=4.5 may be too great for non-linear damping. When compared to experimental values of Table 19 [7], where δ=4.5 corresponds to B_3=0.75, it is ten times greater than the experimental values at best.

F_n	COEF.	ore carrier	tanker	container	cargo ship
0	$\hat{B}_1$	0.00308	0.00209	0.00082	0.00061
	$\hat{B}_2$	0.03262	0.04168	0.03690	0.04908
	$\hat{B}_3$	0.12170	0.03877	0.08474	0.08994
0.10	$\hat{B}_1$	0.00359	0.00316		
	$\hat{B}_2$	0.04110	0.04453		
	$\hat{B}_3$	0.07783	0.03581		
0.15	$\hat{B}_1$		0.00344	0.00374	0.00242
	$\hat{B}_2$		0.04254	0.02531	0.03755
	$\hat{B}_3$		0.05524	0.09835	0.08755
0.20	$\hat{B}_1$				0.00332
	$\hat{B}_2$				0.03551
	$\hat{B}_3$				0.05226
0.25	$\hat{B}_1$			0.00628	0.00389
	$\hat{B}_2$			0.02125	0.04033
	$\hat{B}_3$			0.03567	0.02206
0.275	$\hat{B}_1$			0.00671	
	$\hat{B}_2$			0.01402	
	$\hat{B}_3$			0.05097	

Table 19: Experimental values of roll damping coefficients for various ship types and Froude numbers [7]

V.4.5 Conclusions

Both Level 1 and level 2A criteria for parametric rolling seem to fulfil their purposes adequately. Level 1 vulnerability check requires hydrostatic calculation of GM on the span of wave with λ=L and s_w=0.0167. This calculation is simple and conservative enough in order to let the ships which are not prone to parametric rolling (e.g. tankers) pass the check easily. Level 2A check follows the same hydrostatic concept but it also includes a risk-based approach by utilizing the probability of each wave occurrence. It should be mentioned however, that the use of the speed V_{PR} which corresponds to principal resonance does not exclude the existence of parametric rolling and, thus, is not necessary for a level 2A check.

On the other hand, level 2B criterion faces two important issues. The first one involves the inconsistencies which occur between the various methods and parameters used. The draft regulation suggests the solution of non-linear parametric rolling differential equation without explicitly defining the procedure followed. As shown in Figure 20, where 3 different methods that comply with the regulation (with the exception of non-linear damping) are used, different results and inconsistencies between index values may occur. Moreover, initial conditions, time span of the solution and the method used to extract the amplitude from time domain history are not mentioned at all. As shown in Figure 24, different initial conditions may lead to different dynamic characteristics while extraction of roll amplitude from roll history may be vague in some occasions, as seen for example in Figure 22. Consequently, validation between various applications is unlikely.

The second issue is related to how the criterion tends to become less conservative in level 2B for no apparent reason. As stated in V.4.2, the use of the waves with the characteristics of Table 16 leads to lower values of 2B index since many of those waves have zero probability of occurrence. At the same time, a weighted average of 7 different wave heading angles is used which reduces the index values even further since almost beam seas are considered where parametric rolling is inexistent. Furthermore, as stated in V.4.2, parametric rolling equations suggested by the draft regulation are not capable of simulating any seas other than heading and following since wave excitation is not included.. Thus, results for the rest of the wave angles are not credible but still contribute to the reduction of the index value. Non-linear roll damping also attributes to this reduction since the procedure suggested by the draft leads to far greater values than those that originated from experiments.

To sum up, draft regulation for parametric rolling stability failure requires some further development and consideration. Formulation of clear requirements is essential for valid applications to be achieved. Meanwhile, the issues mentioned in the previous paragraphs should be addressed, in an effort to receive credible results and realistic simulations.

CHAPTER VI

Surf-Riding/Broaching

V.1 Physical background

Surf-riding is the phenomenon during which, a ship sailing through following waves is captured by a specific wave and forced to travel at its celerity. It often leads to a sudden uncontrollable turn that causes the ship to heel. This uncontrollable turn is called broaching. Since surf-riding is a prerequisite for broaching, second generation stability criteria and this diploma thesis focus on surf-riding only.

We can assume that during surf riding, the ship is in equilibrium under the effects of wave excitation, propeller thrust and resistance while it sails at wave celerity, as is shown in Figure 31.

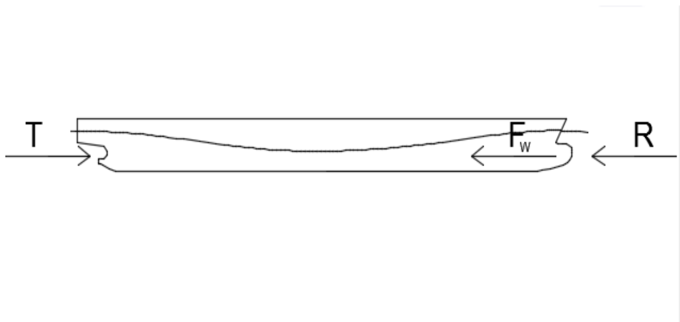


Figure 31: Surf-riding equilibrium

The sum of all forces must equal to zero. This condition creates two points of equilibrium on the span of a wave as shown in Figure 32.

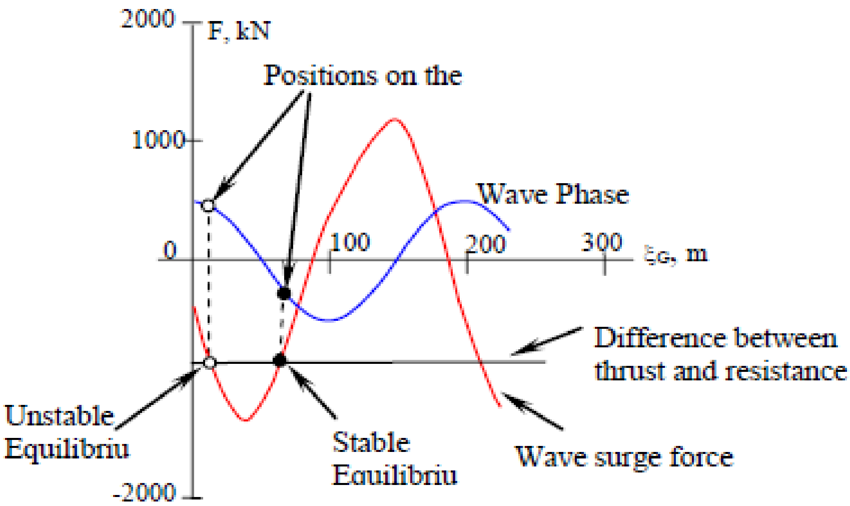


Figure 32: Surf-riding forces on the span of a wave [20]

The first point near the peak of the wave is unstable. That means that the slightest perturbation would free the ship from the wave's grasp and let it sail at its design speed. On the other hand, the second point of equilibrium near the wave trough is stable and the ship would return to this point under any perturbation.

Surf riding equilibrium does not exclude the probability of surging. As shown in phase diagram of Figure 33, the regions of surging and surf-riding coexist. For a certain initial pair of the ship's forward speed and its position on the wave, surf-riding or surging may occur.

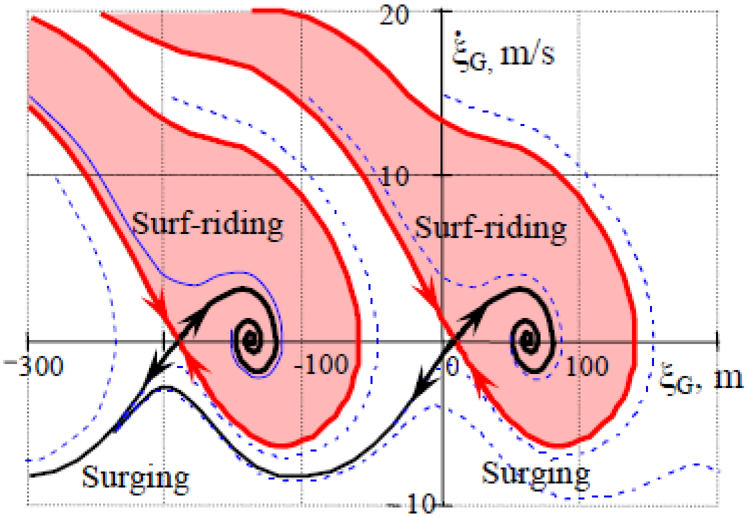


Figure 33: Phase plane for surf-riding [20]

The phase plane of Figure 33 corresponds to a specific forward speed that allows the existence of surf-riding. For lower speeds the red regions of surf-riding may disappear. The critical speed at which those regions appear (or disappear) is called <u>surf-riding threshold under certain initial conditions</u>. For greater values of forward speed, surf-riding regions meet one another and, as a result, regions of surging disappear and surf-riding occurs for any point on the phase plane. The critical speed at which this happens is called <u>surf-riding threshold under any initial conditions.</u>

In order to locate the first threshold, the surging equation of equilibrium could be solved relative to propeller revolutions n, considering the forward speed to be equal to wave celerity c:

$$T(c,n) = R(c,n) + F_W \qquad \textbf{[VI.1]}$$

Where R is resistance in calm water, T is the propeller thrust and F_W is the wave excitation. Assuming that wave excitation includes only the Froude-Krylov components we receive:

$$F_W = \rho g k \zeta_A \sqrt{A_S^2 + A_C^2} \qquad \textbf{[VI.2]}$$

Where:

$$A_S = \int_{-0.5L}^{0.5L} A_0(x)\cos(kx)dx \ , \ A_C = \int_{-0.5L}^{0.5L} A_0(x)\sin(kx)dx \quad \textbf{[VI.3]}$$

$$A_0(x) = 2\int_{d(x)}^{0} y(x,z)\exp(kz)dz \quad \textbf{[VI.4]}$$

Where d(x) is the draft at longitudinal position x.

However straightforward the calculation of the first threshold may be, this is not the case for the second one. A popular method (that is also used by the criterion) for locating the second threshold of surf-riding is Melnikov's method.

The uncoupled surging equation used by [25] is:

$$[m - X_{\dot{u}}(U;\lambda)]\dot{U} = [T(x,U;n;Ak,\lambda) - R(x,U;Ak,\lambda)] - X_W(x;Ak,\lambda) \quad \textbf{[VI.5]}$$

Where m is the ship's displacement, $X_{\dot{u}}$ is surge added mass, *U* is the forward velocity, *T* is propeller thrust, *R* is the ship's resistance in calm water, n is the propeller revolutions, *x* is the longitudinal distance between the ship's centre of gravity and the trough of the investigated wave with steepness *Ak* and length *λ*. After a few transformations, equation VI.5 becomes:

$$y'' + p_1 y' + p_2 y'^2 + p_3 y'^3 + \sin y = \frac{r}{q} \quad \textbf{[VI.6]}$$

Where $y = kx$, p_1, p_2, p_3 are coefficients related to the difference between thrust and resistance and $\frac{r}{q}$ is the ratio of the difference between thrust and resistance and the wave surging force. Melnikov's function then becomes:

$$\frac{r}{q} = -\frac{4}{\pi} p_1 + 2p_2 - \frac{32}{3\pi} p_3 \quad \textbf{[VI.7]}$$

Melnikov's function represents the distance between surf-riding regions (red regions in Figure 33). When the vessel's speed reaches the second threshold, the distance between those two regions is zero as they become tangent to each other. Consequently, by setting Melnikov's function equal to zero we create an algebraic equation whose solution gives the critical number of propeller revolutions n_{cr}. When n_{cr} is surpassed, surf-riding under any initial conditions occurs.

VI.2 Draft Regulation

In this chapter, draft regulation of surf-riding stability failure is presented, in accordance with Annex 32 of [13].

This regulation is to be applied to all ships of length equal to 24 meters or greater. The following paragraphs contain draft regulations extracted from Annex 32 of [13].

VI.2.1 Level 1 Vulnerability Criteria

A ship is considered not to be vulnerable to the surf riding/broaching stability failure mode if:

$$L > 200\text{ m} \quad \text{or} \qquad \textbf{[VI.8]}$$

$$Fn < 0.3$$

Where,

- Fn is the Froude number = $V_s / \sqrt{L\ g}$
- V_S is the service speed in calm water (m/s)
- L is the Length of the waterline at the draft corresponding to the loading condition under consideration (m)
- g *is* the gravitational acceleration of 9.81 m/s^2

VI.2.2 Level 2 Vulnerability Criteria

A ship is considered not to be vulnerable to the surf riding/broaching stability failure mode if:

$$C < R_{SR} \qquad \textbf{[VI.9]}$$

Where,

$$C = \sum_{HS}\sum_{TZ}\left(W2(H_S, T_Z)\frac{\sum_{i=1}^{N_\lambda}\sum_{j=1}^{N_a} W_{ij} C2_{ij}}{\sum_{i=1}^{N_\lambda}\sum_{j=1}^{N_a} W_{ij}} \right) \qquad \textbf{[VI.10]}$$

- R_{SR} = 0.0001 or 0.005 is the criterion standard
- $W2(\underline{H_S,\ T_Z})$ is the weighting factor of short-term sea state as a function of the significant wave height, H_S, and the zero-crossing wave period, T_Z. The value of $W2(\underline{H_S,\ T_Z})$ is obtained as the value in Table 20 divided by 100000. The number of short term sea state is 272. Other sources of wave statistics can be used on the discretion of Administration
- W_{ij} is a statistical weight of a wave specified in VI.11 with steepness $(H/\lambda)_j$ and wavelength to ship length ratio $(\lambda / L_{BP})_i$ calculated with the joint distribution of local wave steepness and lengths, which is, with specified discretization N_λ = 80 and N_a = 100. It is given by:

$$W_{ij} = \frac{4\sqrt{g}}{\pi\nu}\frac{L^{5/2}T_{01}}{(H_s)^3} s_j^2 r_i^{3/2}\left(\frac{\sqrt{1+\nu^2}}{1+\sqrt{1+\nu^2}}\right)\Delta r \Delta s \cdot \exp\left[-2\left(\frac{L\cdot r_i \cdot s_j}{H_s}\right)^2 \left\{1+\frac{1}{\nu^2}\left(1-\sqrt{\frac{gT_{01}{}^2}{2\pi r_i\ L}}\right)^2\right\}\right] \textbf{[VI.11]}$$

Where,

- ν = 0.4256
- *L* is the length between perpendiculars (m)
- T_{01} = 1.086 T_Z
- s_j = $(H/\lambda)_j$ is the wave steepness which varies from 0.03 to 0.15 with the increment Δs = 0.0012
- r_i = $(\lambda/L)_i$ is the wavelength to ship length ratio which varies from 1.0 to 3.0 with the increment Δr = 0.025.

The value of $C2_{ij}$ is calculated for each wave as follows:

$$C2_{ij} = \begin{cases} 1 & if \quad Fn > Fn_{cr}(r_j, s_i) \\ 0 & if \quad Fn \le Fn_{cr}(r_j, s_i) \end{cases} \qquad \textbf{[VI.12]}$$

Where, Fn_{cr} is the critical Froude number corresponding to the threshold of surf-riding (surf-riding occurs under any initial condition) for the regular wave with steepness s_j and wave length to ship length ratio r_i.

The critical Froude number, Fn_{cr}, is calculated using the following formula:

$$Fn_{cr} = u_{cr} / \sqrt{L\,g}\,, \qquad \textbf{[VI.13]}$$

Where,

- u_{cr} is the critical ship speed (m/s) determined by solving the surge equation with the critical propulsor revolutions, n_{cr}, by using a numerical iteration method
- *L* is the length between perpendiculars (m)
- *g* is the gravitation acceleration of 9.81 m/s^2

T_z (s) ▶ / 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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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

Table 20: Wave occurrences per 100,000 observations for surf-riding evaluation

The critical ship speed, u_{cr}, is determined by solving the following equation with the critical propulsor revolutions, n_{cr}, by using a numerical iteration method:

$$T_e(u_{cr};n_{cr}) - R(u_{cr}) = 0 \qquad \textbf{[VI.14]}$$

Where,

- $R(u_{cr})$ is the calm water resistance of the ship at the ship speed of u_{cr}
- $T_e(u_{cr};n_{cr})$ is the thrust delivered by the ship's propeller in calm water
- n_{cr} is the commanded number of revolutions of propeller corresponding to the threshold of surf-riding (surf-riding occurs under any initial conditions)

Calm water resistance, $R(u)$, is approximated based on available data with a polynomial which may, but need not, include terms up to the 5th power. The Administration may establish specific requirements on approximation of the ship's resistance to be considered:

$$R(u) = r_1 u + r_2 u^2 + r_3 u^3 + r_4 u^4 + r_5 u^5 \qquad \textbf{[VI.15]}$$

Where,

- u is a speed of the ship (m/s) in calm water
- r_1, r_2, r_3, r_4, r_5 are the approximation coefficients for the calm water resistance

For a ship using one propeller as the main propulsor, the propulsor thrust, $T_\varepsilon(u;n)$ in calm water may be approximated using second power polynomial:

$$T_e(u;n) = (1-t_p)\rho n^2 D_p{}^4 \left\{\kappa_0 + \kappa_1 J + \kappa_2 J^2\right\} \qquad \textbf{[VI.16]}$$

Where,

- u is a speed of the ship (m/s) in calm water
- n is the commanded number of revolutions of propulsor (1/s)
- t_p is the approximate thrust deduction
- w_p is the approximate wake fraction
- D_p is the propeller diameter (m)
- κ_0, κ_1, κ_2 are the approximation coefficients for the propeller thrust coefficient in calm water
- $J = \dfrac{u(1-w_p)}{nD_P}$ is the advance ratio
- ρ is the density of salt water (1025 kg/m^3)

For a ship using a propulsor other than a propeller, the propulsor thrust may be to be evaluated by a method appropriate to the type of propulsor used to satisfaction of the Administration.
The amplitude of wave surging force is calculated as:

$$f = \rho g k \frac{H}{2} \sqrt{F_C^2 + F_S^2} \text{ (N)} \qquad \textbf{[VI.17]}$$

Where,

- ρ is the density of salt water (1025 kg/m^3)
- g is the gravitation acceleration of 9.81 m/s^2
- k_i is the wave number = $\dfrac{2\pi}{r_i L}$ (1/m)
- H_{ij} is the wave height = $s_j r_i L$ (m)
- F_C = $\sum_{i=1}^{N} \Delta x_i S(x_i) \sin kx_i \exp\left(-0.5k \cdot d(x_i)\right)$ (m^3)
- F_S = $\sum_{i=1}^{N} \Delta x_i S(x_i) \cos kx_i \exp\left(-0.5k \cdot d(x_i)\right)$(m^3)

  F_C and F_S are parts of the Froude-Krylov component of the wave surging force
- x_i is the longitudinal distance from the centre of ship mass to a station (m), positive for a bow section
- $d(x_i)$ is the draft at station i in calm water (m)
- $S(x_i)$ is the area of submerged portion of the ship at station i in calm water (m^2)
- N is the of number of stations

Other components of wave surging force may be included at the discretion of the Administration

The critical number of revolutions of the propulsor corresponding to the surf-riding threshold, n_{cr}, may be calculated using a numerical iteration method, for which a particular form of the equation depends on the approximation of resistance in calm water. Recommended numerical iteration methods include Melnikov's method as formulated in [15].

According to Annex 35 of [13], the critical number of revolutions corresponding to global surf-riding threshold, n_{cr}, can be calculated by solving the following equation:

$$2\pi \frac{T_e(c_w;n) - R(c_w)}{f} = \sum_{i=1}^{N} \sum_{j=1}^{i} C_{ij} (-2)^j I_j \quad \textbf{[VI.18]}$$

Where,

- T_e is propeller's thrust, $T_e(u;n) = (1-t_p)\rho n^2 D_p^4 K_T(J)$
- N is the number of the order of thrust and resistance polynomial equations
- C_{ij} is a coefficient given by $C_{ij} = \dfrac{c_i}{fk^j} \left(\dfrac{i!}{j!(i-j)!} \right) \dfrac{(fk)^{j/2}}{(m+m_x)^{j/2}} c_w^{i-j}$

Where,

- f is the amplitude of wave surge force
- $c_i = -\dfrac{(1-t_p)(1-w_p)^i \rho \kappa_\iota}{n^{i-2} D_p^{i-4}} + r_i$

- $k = \dfrac{2\pi}{\lambda}$ is the wave number
- *m*, m_x are the ship's mass and added mass respectively (kg)
- $c_w = \sqrt{\dfrac{g}{k}}\sqrt{1+(k\zeta_a)^2}$ is the wave celerity (m/s)

- $I_j = 2\sqrt{\pi}\,\Gamma\left(\dfrac{j+1}{2}\right) / \Gamma\left(\dfrac{j+2}{2}\right)$

Where,

- $\Gamma(\mathrm{N}) = (\mathrm{N}-1)!$
- $\Gamma(\mathrm{N}+\frac{1}{2}) = (2\mathrm{N}-1)!!\dfrac{\sqrt{\pi}}{2^{\mathrm{N}}}$

VI.3 Application

Surf riding is a phenomenon that appears almost exclusively to small vessels. As a result, for the application of this criterion a purse seiner fishing vessel is used. Its main perpendiculars are:

Length L_{BP} (m)	34.5
Beam (m)	7.6
Depth (m)	3.07
Mean Draught (m)	2.99
Block Coefficient	0.652
GM (m)	0.755
Design Speed (knots)	13.8
Length of waterline (m)	36.534
Froude Number	0.3747

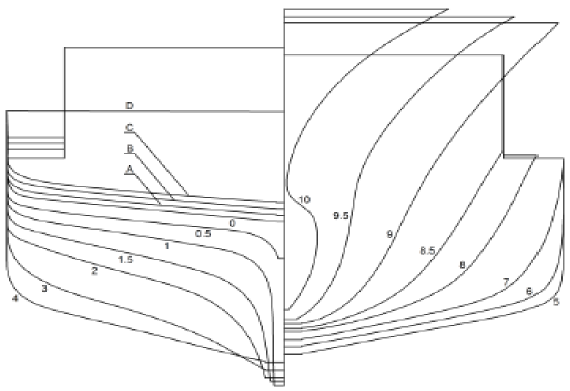


Figure 34a: Purse-seiner body plan **Figure 34b: Submerged hull of Purse-seiner**

VI.3.1 Level 1 Vulnerability Check

Level 1 vulnerability check is a simple check of ship length and Froude number. In our case, L=34.5m<200 and F_N=0.3747>0.3. Therefore, level 1 vulnerability is detected.

VI.3.2 Level 2 Vulnerability Check

Level 2 vulnerability check requires application of Melnikov's method. First, we will need the resistance curve in calm water which is:

$$R(u) = 5950.96u - 2334.25u^2 + 609.78u^3$$

Where u is the ship's forward speed. The characteristics of the propeller are shown next:

Thrust deduction t_p=0.147
Wake fraction w_p=0.142
Propeller diameter D=2.6m
Approximation coefficients for propeller thrust coefficient in calm water:
k_0= 0.322506
k_1= -0.208699
k_2= -1.22576

Then the thrust curve is:

$$T(n,J) = 39954.6n^2(0.322506 - 0.208699J - 1.22576J^2)$$

Where n are the propeller revolutions and $J = \dfrac{u(1-w_p)}{nD_p}$ is the advance ratio.

Calculation of surging Froude-Krylov forces requires the estimation of the area of each section. For our ship 19 sections are used. Their sectional areas for our design draft are shown in Table 21.

Section	Longitudinal Position (m)	Sectional Area(m^2)
d	-21.65	0.0712
c	-20.55	9.564764
b	-19.45	9.797107
a	-18.35	9.909627
0	-17.25	10.05533
0.5	-15.525	10.90235
1	-13.8	19.81088
1.5	-12.075	23.59998
2	-10.35	25.34969
3	-6.9	28.06233
4	-3.45	29.60159
5	0	29.3616
6	3.45	28.32056

Section	Longitudinal Position (m)	Sectional Area (m^2)
7	6.9	26.58798
8	10.35	23.12281
8.5	12.075	20.62198
9	13.8	19.49168
9.5	15.525	12.69921
10	17.25	5.338333

Table 21: Sectional areas for ship under investigation

Melnikov's method is used in order to detect the critical number of revolutions n_{cr} corresponding to global surf-ring threshold. Then, VI.18 is solved and the critical speed for surf-riding is calculated which corresponds to a critical Froude number. If the Froude number which corresponds to design speed is greater than critical Froude number then surf-riding occurs. This check is carried out for 100x80=8000 different waves. In our case, surf riding is detected for waves with steepness s and dimensionless wave length r = λ/L, as shown in Figure 35.

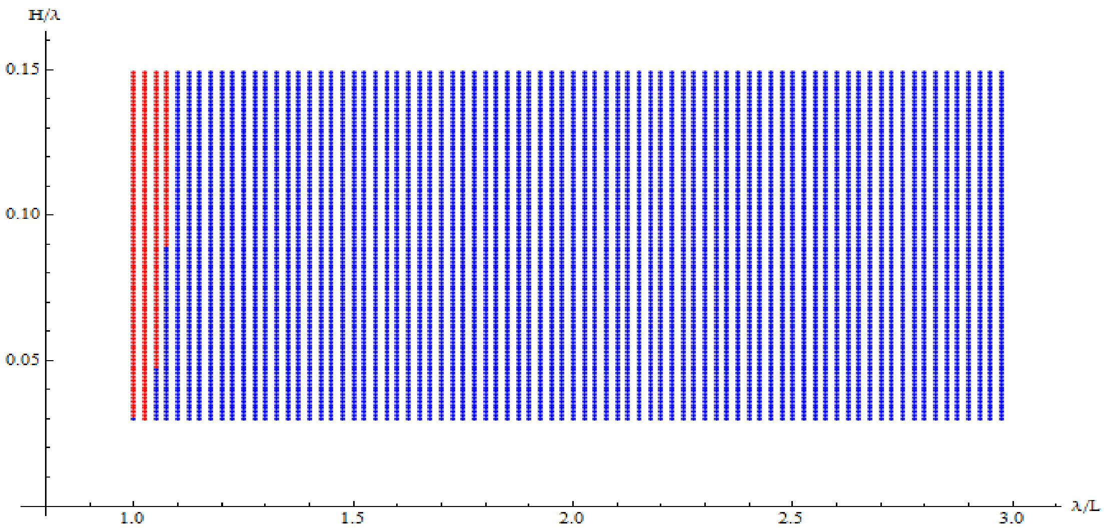


Figure 35: Surf-riding detection (red points) for all waves under consideration (V=13.8kn)

The criterion index C for the loading condition under consideration is:

$$C = 0.386 > 0.005$$

Which means that surf-riding vulnerability is detected. A direct stability assessment would be required next in order to achieve compliance with the regulation. However, if the vessel speed is reduced, for example by 1 knot at 12.8 knots surf riding is not detected any more, as shown in Figure 36.

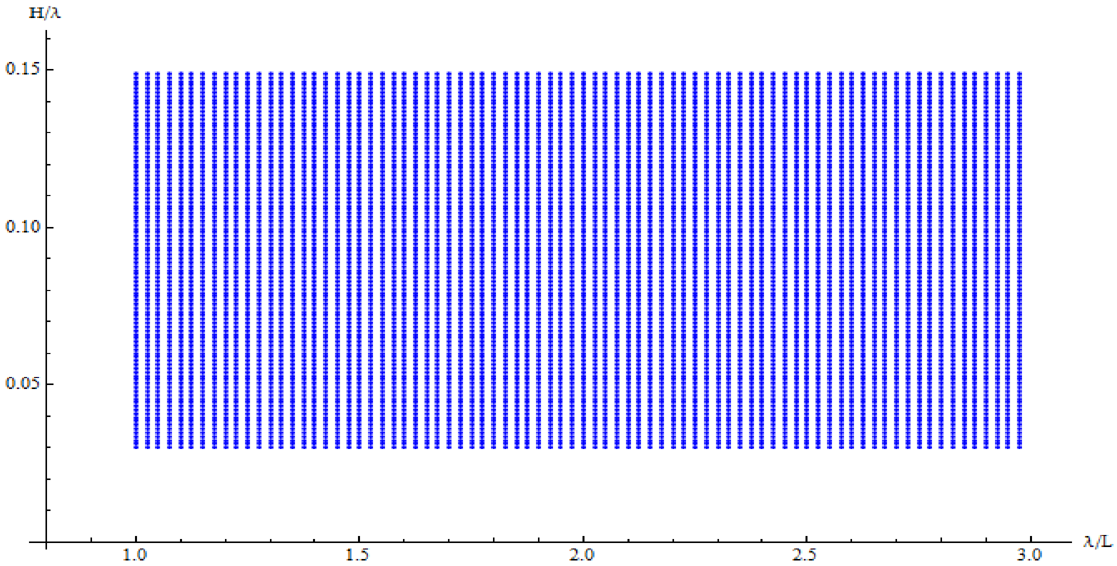


Figure 36: Surf-riding detection (red points) for all waves under consideration (V=12.8kn)

Then, the criterion index C is reduced to zero (C=0) and level 2 vulnerability is avoided.

VI.4 Evaluation

Level 1 vulnerability check originates from a guidance introduced by MSC.707 in 1995. According to this guidance, surf-riding occurs for a wave with steepness s=0.1 if the following condition regarding the vessel speed is fulfilled:

$$V_S \geq \frac{1.8\sqrt{L}}{\cos(180-a)} \qquad \textbf{[VI.19]}$$

Where α is wave heading angle (180 for following seas). For following waves this speed corresponds to the following Froude number:

$$Fn \geq \frac{0.5144 \cdot 1.8\sqrt{L}}{\cos(180-180)\sqrt{gL}} = \frac{0.926}{\sqrt{g}} = 0.296 \approx 0.3 \qquad \textbf{[VI.20}$$

Considering the conservative steepness of 1/10 and the existence of this regulation as a guidance to shipmasters, it makes sense that it would be used as a level 1 criterion.

Level 2 vulnerability check uses Melnikov's method which has been regarded as a valid way for detecting surf-riding threshold. The formulation of the method for the Level 2 criterion is based on the works of [15] and [25]. For each wave with dimensionless length r_i and steepness s_j Melnikov's methods has been implemented in order to calculate the critical Froude numbers. When the achieved Froude number is larger than the critical value, surf riding under any initial condition occurs. Consequently, a simple way to avoid vulnerability is to reduce the design speed of the vessel.

According to Figure 37, the most dangerous waves are those for which their length is equal to the length of the ship, as we expected. Moreover, increasing wave steepness leads to lower values of critical Froude number as shown in Figure 28.This effect is stronger for wave lengths closer the ship's length. These results agree with other works where Melnikov's method is applied for the detection of surf-riding threshold.

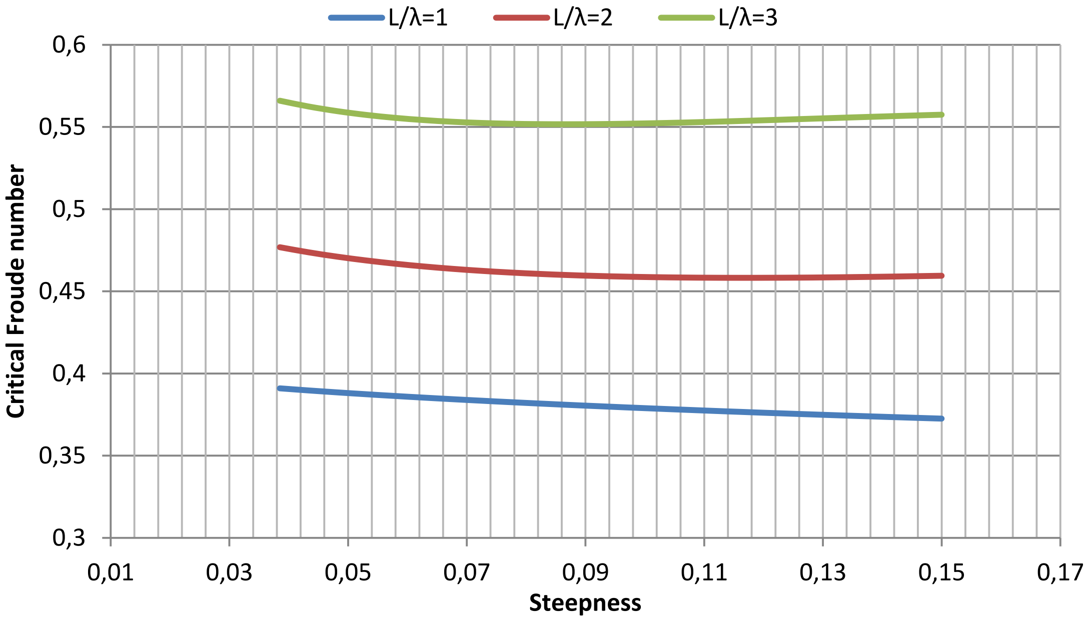


Figure 37: Effect of steepness on critical Froude number

Overall, surf-riding criterion could be regarded as capable of evaluating a ship's vulnerability to surf-riding adequately. Its parameters are explicitly defined and the methodology followed has been applied in multiple works and is considered valid, yet simple enough for a level 2 check.

CHAPTER VII

Excessive Accelerations

VII.1 Physical Background

Large angles of rolling may lead to extreme lateral accelerations, especially for superstructures of great height, such as a container ship's bridge or highest accommodation deck. Those accelerations are often the cause of accidents regarding tipping of sailors which may lead to injuries or loss of life [24]. They often take place for loading conditions with low metacentric heights, such as ballast conditions or conditions with heavy homogenous cargo.

According to [24], the following model is used for the criterion:

The ship is assumed to sail under the effect of harmonic rolling with steady amplitude. The response is expressed by the following equation:

$$\varphi = \varphi_{\alpha} \sin \omega t \qquad \textbf{[VII.1]}$$

Where φ_{α} is the rolling amplitude and ω is the roll frequency. A random point that exists h meters above the roll axis R, is under the effect of the following accelerations, as shown in Figure 24.

- Acceleration α_{φ} due to roll motion that is perpendicular to the roll radius of the point under investigation.
- Vertical acceleration α_{v} due to heave and pitch motions.
- Lateral acceleration α_{h} due to yaw motions.
- Gravitational acceleration g.

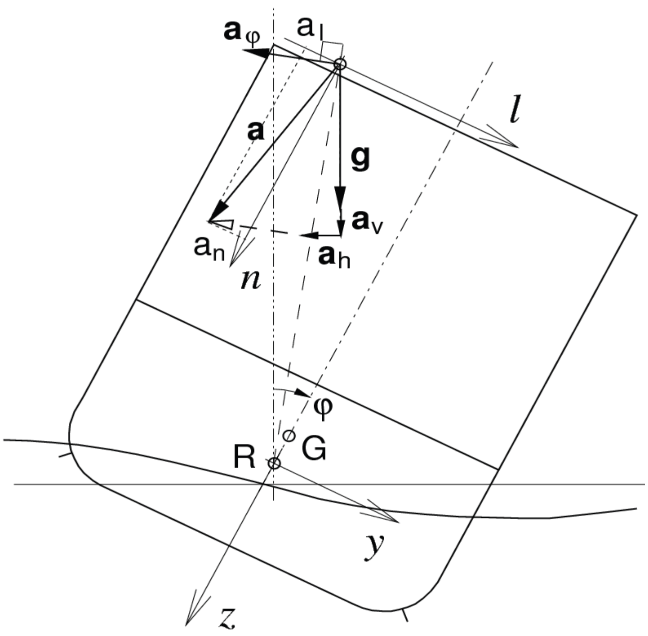


Figure 38: Different accelerations of the investigated point [24]

Centrifugal and Coriolis accelerations are neglected. A person is also under the effect of frictional lateral acceleration provided by the feet α_l. The sum of all accelerations leads to acceleration vector $\boldsymbol{\alpha}$.

Roll angular acceleration is given by:

$$\ddot{\varphi} = -\varphi_\alpha \omega^2 \sin \omega t \quad \textbf{[VII.2]}$$

The projections of acceleration $\boldsymbol{\alpha}$ on y, z axes which are fixed on the ship are:

$$\begin{aligned} a_y &= (g + a_v)\sin\varphi + h\omega^2\varphi \\ \alpha_z &= (g + a_v)\cos\varphi - y\omega^2\varphi \end{aligned} \quad \textbf{[VII.3]}$$

Where *h, y* are the distances of the investigated point from z, y axes respectively. The maximum values of α_y, α_z occur for the maximum value of roll angle, therefore assuming $\varphi=\varphi_\alpha$ we receive:

$$\begin{aligned} a_y &= (g + a_v)\sin\varphi_a + h\omega^2\varphi_a \\ \alpha_z &= (g + a_v)\cos\varphi_a - y\omega^2\varphi_a \end{aligned} \quad \textbf{[VII.4]}$$

In order to calculate roll amplitude φ_a the following model is used:

$$I_\varphi\ddot{\varphi} + b_\varphi\dot{\varphi} + c_\varphi\varphi = \mathrm{M}\sin(\omega_e t) \quad \textbf{[VII.5]}$$

where I_φ is roll moment of inertia, b_φ is roll damping coefficient, ω_e is encounter frequency, M is amplitude of wave excitation and $c_\varphi = mg\,GM$ is linear restoring coefficient, where m is ship's displacement and GM is the initial metacentric height in calm water.

By neglecting diffraction forces, the amplitude of wave excitation can be written as:

$$M = ka_w mgGM \sin\mu \quad \textbf{[VII.12]}$$

Where k is the coefficient of wave excitation reduction due to finite wave length, α_w is effective wave slope and μ is the direction of the waves.

According to [24], accidents regarding excessive lateral accelerations occur for low speed settings and thus, we assume that $\omega_e=\omega$ where ω is wave frequency. Then, roll equation VII.5 becomes:

$$I_\varphi\ddot{\varphi} + b_\varphi\dot{\varphi} + mgGM = \mathrm{k}\,\mathrm{a}_\mathrm{w}\, mgGM \sin\mu \sin(\omega\, t) \quad \textbf{[VII.7]}$$

If we set $I_\varphi = mk_\varphi^2$ where k_φ is radius of gyration and $\delta = \pi b_\varphi / (\omega_0 I_\varphi)$ we receive:

$$k_\varphi^2\ddot{\varphi} + (\delta/\pi)\omega_0 k_\varphi^2\dot{\varphi} + gGM = \mathrm{k}\,\mathrm{a}_\mathrm{w}\, gGM \sin\mu \sin(\omega\, t) \quad \textbf{[VII.8]}$$

Solution of VII.8 is a harmonic roll motion with amplitude φ_α:

$$\frac{\varphi_\alpha}{\zeta_\alpha} = \frac{k\omega^2\omega_0^2 \sin\mu}{g[(\omega_0^2 - \omega^2)^2 + \omega^2\omega_0^2(\delta/\pi)^2]^{1/2}} \quad \textbf{[VII.9]}$$

Where $\zeta_\alpha = \alpha_w \lambda_w / (2\pi)$ is the wave amplitude and λ_w is the wave length. By neglecting lateral acceleration due to yaw (a_v=0) and assuming $\sin\varphi_\alpha = \varphi_\alpha$ we receive from VII.4:

$$a_y = \varphi_a (g + h\omega^2) \quad \textbf{[VII.10]}$$

By substituting the value of φ_α we could receive the expression of the lateral acceleration α_y that occurs under the effect of a harmonic wave with ζ_α and λ_w. However, due to the random nature of the problem, it would be wiser to use the variance of roll amplitude σ_φ^2 for a sea state with spectrum S(ω):

$$\sigma_\varphi^2 = \int_0^\infty \int_0^{2\pi} \left(\frac{\varphi_\alpha}{\zeta_\alpha} \right)^2 D(\mu - \mu_0) S_\zeta(\omega) d\omega d\mu \quad \textbf{[VII.11]}$$

By substituting VII.9 in VII.11 we receive:

$$\sigma_\varphi^2 = \frac{\omega_0^4}{g^2} \int_0^{2\pi} D \sin^2 \mu d\mu \int_0^\infty \frac{k^2 \omega^4 S d\omega}{(\omega_0^2 - \omega^2)^2 + \omega_0^2 \omega^2 (\delta / \pi)^2} \quad \textbf{[VII.12]}$$

Then, the value of σ_φ^2 can be used as a measurement of a ship's vulnerability to excessive lateral accelerations.

For fewer calculations, a simpler equation could be extracted from σ_φ^2. Firstly, the following transformation is made:

$$I_1 = \int_0^{2\pi} D \sin^2 \mu d\mu \quad \textbf{[VII.13]}$$

By assuming that $\omega = \omega_0$, which is the frequency that maximises the acceleration, we receive:

$$\sigma_\varphi^2 = \frac{\omega_0^4}{g^2} I_1 \int_0^\infty \frac{k^2 \omega^4 S d\omega}{(\omega_0^2 - \omega^2)^2 + \omega_0^2 \omega^2 (\delta / \pi)^2} \approx \omega_0^4 I_1 \pi^2 k^2 \omega_0 S(\omega_0) / (2\delta g^2) \quad \textbf{[VII.14]}$$

According to [24], the relation between I_1 and wave heading is shown in Figure 39. Considering the most dangerous wave heading angles to be 120 and 150 degrees as observed by [24], an average value of I_1 could be equal to 0.5. Finally we receive:

$$\sigma_\varphi^2 = 0.0256 \omega_0^5 k^2 S(\omega_0) / \delta \quad \textbf{[VII.15]}$$

This calculates a conservative acceleration that is used for Level 1 vulnerability criterion.

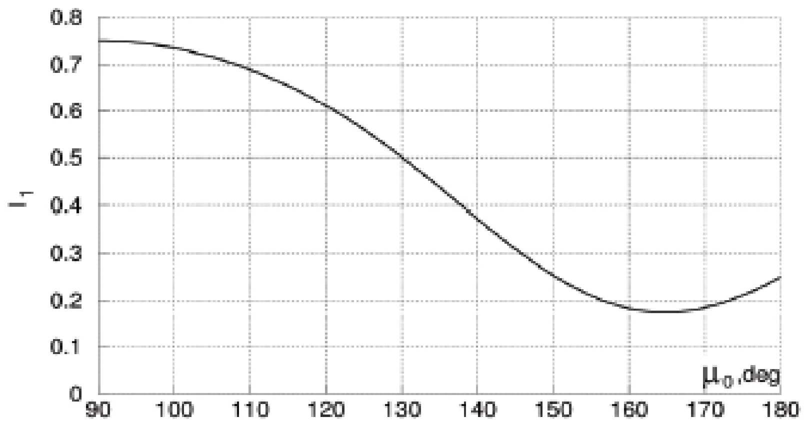


Figure 39: Value of first integral (I_1) for each wave heading angle

VII.2 Draft Regulation

In this chapter, draft regulation of surf-riding stability failure is presented, in accordance with Annex 33 of [13].

This regulation is to be applied to all ships of length equal to 100 meters or greater. The following paragraphs contain draft regulations extracted from Annex 33 of [13].

VII.2.1 Level 1 Vulnerability Criteria

The criterion is to be applied to the highest locations along the ship where passengers or crew members may be present. Areas that are entered occasionally may be dispensed. Loading condition is considered as not vulnerable to excessive lateral accelerations if for all considered locations the following condition is satisfied:

$$\varphi k_L (g + 4\pi^2 H / T_r^2) < R_1 \qquad \textbf{[VII.16]}$$

Where φ(rad) is the characteristic roll amplitude, k_L is a non-dimensional factor taking into account vertical accelerations and yaw motion, g = 9.81 m/ s^2 is the gravity acceleration, H(m) is the height of the bridge deck above the roll axis, T_r(s) is the natural roll period and R_1(m/s^2) is the standard for lateral acceleration.

OPTION A

The value of standard is defined as R_1 = 5.9 m / s^2 for ships with the length between perpendiculars greater than 250.0 m and R_1 = [X.X] m / s^2 for ships with the length between perpendiculars less than 250.0 m. For ships with the length between perpendiculars less than 100.0 m, the excessive acceleration criteria are not applicable.

OPTION B

The value of standard is defined as R_1 = 7.848 m/s^2 for ships with the length between perpendiculars greater than 250.0 m and R_1 = [X.X] m / s^2 for ships with the length between perpendiculars less than 250.0 m. For ships with the length between perpendiculars less than 100.0 m, the excessive acceleration criteria are not applicable.

Factor k_L is defined as follows:

$k_L = 1.125 - 0.625x / L$, if $x < 0.2L$
$k_L = 1.0$, if $0.2L \le x \le 0.65L$
$k_L = 0.527 + 0.727x / L$, if $x > 0.65$

Where x (m) is the longitudinal distance from the aft perpendicular to the considered location, and L (m) is the length between perpendiculars. The natural roll period T_r(s), is defined as follows:

$$T_r = 2C \cdot B / GM^{0.5} \qquad \textbf{[VII.17]}$$

Where:

$$C = 0.373 + 0.023(B / T) - 0.043(L_{WL} / 100) \qquad \textbf{[VII.18]}$$

B (m) is the moulded breadth of the ship, T(m) is the mean moulded draught of the ship, L_{WL} (m) is the length of the ship at waterline and GM (m) is the initial metacentric height corrected for the free surface effects.

Alternatively, natural roll period may be defined for any ship using methods for the natural roll period from the Level 2 or Direct Assessment for Excessive Accelerations, or from model tests carried out according to MSC.1/Circ.1200 or alternative test procedures approved by the Administration.

The height of the considered location above the roll axis H is defined, assuming the roll axis at the mean height between the waterline and the centre of gravity of the ship.

The characteristic roll amplitude, rad, is defined as:

OPTION A

$$\varphi = 2.951 rs / \delta_\varphi^{0.5} \qquad \textbf{[VII.19]}$$

Where r is the non-dimensional effective wave slope, s is the non-dimensional wave steepness and δ_φ is the non-dimensional logarithmic decrement of roll decay. The effective wave slope r is defined as follows:

$$r = \frac{K_1 + K_2 + OG \cdot F}{\frac{B^2}{12 C_B T} - \frac{C_B T}{2} - OG} \qquad \textbf{[VII.20]}$$

where,

$$K_1 = g\beta T_r^2(\tau + \tau\tilde{T} - 1/\tilde{T})/(4\pi^2)$$
$$K_2 = g\tau T_r^2(\beta - \cos\tilde{B})/(4\pi^2)$$
$$F = \beta(\tau - 1/\tilde{T})$$
$$OG = KG - T$$
$$\beta = \sin(\tilde{B})/(\tilde{B})$$
$$\tau = \exp(-\tilde{T})/\tilde{T}$$
$$\tilde{B} = 2\pi^2 \mathrm{B}/(T_r^2)$$
$$\tilde{T} = 4\pi^2 C_B T/(gT_r^2)$$

Logarithmic decrement of roll decay δ_φ is defined as follows:

$$\delta_\varphi = 0.267 + 0.668 \cdot 100A_{BK}/(L_{WL} \cdot B), \text{ if } C_m > 0.96$$
$$\delta_\varphi = 0.267 + (16.690 \cdot C_m - 15.355) \cdot 100A_{BK}/(L_{WL} \cdot B), \text{ if } 0.94 < C_m < 0.96$$
$$\delta_\varphi = 0.267 + 0.334 \cdot 100A_{BK}/(L_{WL} \cdot B), \text{ if } C_m < 0.94$$

Where, $100A_{BK}/(L_{WL}\ B)$ shall not exceed 4.0 and C_m is the non-dimensional midship section coefficient.

For a ship with sharp bilge, δ_φ is taken equal to 2.937. A_{BK} is the bilge keel area, defined in the same way as in the Vulnerability Criteria Level 1 for parametric roll.

OPTION B

$$\varphi = 109kX_1X_2\sqrt{rs}\pi/180 \qquad \textbf{[VII.21]}$$

Where the factors k, X_1 and X_2 and the effective wave slope r are defined according to the Weather Criterion, ref. paragraph 2.3.4 of the 2008 Intact Stability Code, and relate to the ship length at waterline, moulded breadth, mean moulded draught, block coefficient, area of bilge keels and KG. All these parameters are defined in the same way as in the Weather Criterion.

Wave steepness s is defined according to the table below:

Tr (s)	s
less than 6.0	0.1
6	0.1
7	0.098
8	0.093
12	0.065
14	0.053
16	0.044
18	0.038
20	0.032
22	0.028

Tr (s)	s
24	0.025
26	0.023
28	0.021
30	0.02
greater than 30	0.02

Table 22: Wave steepness for each natural roll period

VII.2.2 Level 2 Vulnerability Criteria

The criterion is to be applied to the highest locations along the ship where passengers or crew members may be present. Areas that are entered occasionally may be dispensed. Loading condition is considered not vulnerable to excessive lateral accelerations if for all of these locations the condition:

$$P < 10^{-8} \quad \textbf{[VII.22]}$$

is fulfilled, where

$$P = \sum_i w_i \exp[-R_2^2 / (2\sigma_i^2)] \quad \textbf{[VII.23]}$$

With R_2 = 9.81 m / s^2 if the length between perpendiculars is greater than 250.0 m and X.X m/s^2 otherwise. [For ships with the length between perpendiculars less than 100.0 m, excessive acceleration criteria are not applicable.]

The variance of lateral acceleration σ_i^2 is calculated for each of seaways in Table 23 with significant wave height h_{si} and zero-upcrossing period T_{zi} as:

$$\sigma_i^2 = \frac{k_L^2 \omega_r^4 I_1}{g^2} \int_{\omega_1}^{\omega_2} \frac{r^2(\omega) S_\zeta(\omega) \omega^4 (g + H\omega^2)^2 d\omega}{(\omega_r^2 - \omega^2)^2 + \omega_r^2 \omega^2 (\delta_\varphi / \pi)^2} \quad \textbf{[VII.24]}$$

Where, k is a non-dimensional factor taking into account vertical accelerations and yaw motion, depending on the longitudinal position of the considered location, $\omega_r = 2\pi / T_r$ (rad/s) is the natural roll frequency, T(s) is the natural roll period, $I_1 = 0.5$ is a non-dimensional factor taking into account short-crestedness of seaway and helm action, $g = 9.81$ m/ s^2 is the gravity acceleration, r is the non-dimensional effective wave slope, H(m) is the height of the bridge deck above the roll axis, δ_φ is the non-dimensional logarithmic decrement of roll decay, and $\omega_1 = 0.07$ rad/s^2 and $\omega_2 = 0.7$ rad/s^2 are integration limits. Effective wave slope r is equal to the ratio of Froude-Krylov wave exciting moment due to the wave of steepness s from the beam direction to the exciting moment due to the wave of infinite length of the same steepness,

$$r = M / (\pi \cdot s \cdot m \cdot g \cdot GM) \quad \textbf{[VII.25]}$$

The Froude-Krylov wave exciting moment M is calculated by direct integration of hydrostatic pressure in regular beam waves using hydrostatic software and neglecting Smith effect.

Alternatively, simplified analytical formula assuming rectangular section shape can be used as in the Level 1 vulnerability criterion.

The seaway frequency spectrum S_ζ is calculated as ITTC wind sea spectrum,

$$S_\zeta(\omega) = 4.0(h_s / T_z)^2 \exp[-495/(T_z^4 \omega^4)]/\omega^5 \qquad \textbf{[VII.26]}$$

The frequencies of occurrence of seaways w_i are taken from the Table 23 below, which is the same as for parametric rolling evaluation.

	Tz (s) = average zero up-crossing wave period															
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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

Table 23: Wave case occurrences per 100,000 observations for excessive acceleration evaluation

All required parameters may be calculated as shown in Level 1.

VII.3 Application

Vulnerability checks for excessive accelerations will be applied for the same baby post-Panamax container ship used in parametric roll criteria. Its main perpendiculars are:

Length L_{BP} (m)	238.38
Beam (m)	37.3
Depth (m)	19.6
Mean Draught (m)	11.52
Block Coefficient	0.657
Design Speed (knots)	21
Length of waterline (m)	249.85
Froude Number	0.218
Midship coefficient C_M	0.981
Bilge keel area (m^2)	29.67

This time however, we will use a different loading condition. The worst case scenario for excessive lateral accelerations involves large initial metacentric height. For our ship, the loading condition with the highest GM is homogenous with 18tonnes per TEU and initial metacentric height in calm water GM=3.42m. All lateral accelerations will be calculated for a point of the bridge deck with a distance of 33.4m from roll axis. Natural roll period is calculated by using the old formula of weather criterion as suggested in [13]. For the loading condition under investigation $T_0 = 13.6s$.

VII.3.1 Level 1 Vulnerability Check

Level 1 vulnerability check offers two options; Option A requires an achieved lateral acceleration of the investigated point of the ship of less than $5.9m/s^2$. A characteristic roll amplitude has to be estimated by using a deterministic approach as shown in [13]. This amplitude occurs when the ship is under the effect of a wave with steepness s, effective wave slope r and a linear damping coefficient δ_φ. It is given by:

$$\varphi = 2.951rs / \delta_\varphi^{0.5}$$

For midship coefficients greater than 0.96 δ_φ is given by:

$$\delta_\varphi = 0.267 + 0.668 \cdot 100 A_{BK} / (L_{WL} \cdot B) = 0.591$$

Effective wave slope r is given by VII.20 as shown in [13].For our case:

$$K_1 = -3.3$$
$$K_2 = 12.78$$
$$F = -0.8968$$
$$OG = 2.69$$
$$r = 0.7989$$

Wave steepness s for T_0=13.*6s* is given by linear interpolation between values for 12 and 14 seconds. Thus, we receive $s = 0.0554$. Then, estimated roll amplitude is $\varphi = 9.73^o$ and lateral acceleration equal to $2.877m/s^2 < 5.9m/s^2$. Therefore, first option does not detect level 1 vulnerability.

Option B requires an achieved lateral acceleration of less than 7.848m/s^2. For this option, roll amplitude is calculated by using the old formula from weather criterion:

$$\varphi = 109kX_1X_2\sqrt{sr}\pi / 180$$

Parameters X_1, X_2, *k, r, s* are estimated from tables given by weather criterion. For our ship:

$X_1 = 1$
$X_2 = 0.9742$
$s = 0.0554$
$r = 0.73 + \frac{OG}{d} \cdot 0.6 = 0.8701$

Roll amplitude is $\varphi = 23.3^o$ and the achieved lateral acceleration is:

$$6.89 m/s^2 < 7.848 m/s^2$$

Therefore, level 1 vulnerability is not detected by option B either.

However, we will proceed to level 2 vulnerability checks in an effort to ensure the lack of inconsistencies between the two levels.

VII.3.2 Level 2 Vulnerability Check

Level 2 check is more complex and suggests a risk-based approach. As explained before, lateral acceleration is expressed through its variance σ_i^2 which occurs for a wave with height H_i and length λ_i. It is given by:

$$\sigma_i^2 = \frac{k_L^2 \omega_0^4 I_1}{g^2} \int_{\omega_1}^{\omega_2} \frac{r^2(\omega) S_\zeta(\omega) \omega^4 (g + H\omega^2)^2 d\omega}{(\omega_0^2 - \omega^2)^2 + \omega_0^2 \omega^2 (\delta_\varphi / \pi)^2}$$

For our case, $H = 33.4m$, $\omega_0 = 0.462 rad/s$ and the spectrum used is ITTC wind sea spectrum:

$$S_\zeta(\omega) = 4.0(H_i / T_i)^2 \exp[-495/(T_0^4 \omega^4)] / \omega^5$$

The characteristics of the waves under investigation are shown in Table 24.

Wave case	Weight	Wave length	Wave height
N	W_i	λ_i (m)	H_i (m)
1	0.000013	22.574	0.35
2	0.001654	37.316	0.495
3	0.020912	55.743	0.857
4	0.092799	77.857	1.295
5	0.199218	103.655	1.732
6	0.248788	133.139	2.205
7	0.208699	166.309	2.697
8	0.128984	203.164	3.176
9	0.062446	243.705	3.625

Wave case	Weight	Wave length	Wave height
N	W_i	λ_i (m)	H_i (m)
12	0.002473	387.44	4.769
13	0.000658	442.723	5.097
14	0.000158	501.691	5.37
15	0.000034	564.345	5.621
16	0.000007	630.684	5.95

Table 24: Wave characteristics for level 2 check

Effective wave slope r is regarded as a constant and its value is calculated as shown in level 1 Option A and thus, $r = 0.7989$.

Integration limits are $\omega_1 = 0.07 rad/s$, $\omega_2 = 0.7 rad/s$. After integrating for each wave case, the probability of the variance of acceleration exceeding a given standard R_2 is calculated by assuming a Rayleigh distribution:

$$p_i = \exp[-R_2^2 / (2\sigma_i^2)]$$

Where the value of the standard is $R_2 = 9.81 m/s^2$. Then the weighted average of this probability is:

$$P = \sum_i w_i p_i = 7.29x10^{-13} < 10^{-8}$$

Which means that level 2 is consistent with level 1 and no vulnerability is detected.

VII.4 Evaluation

Vulnerability criteria for excessive acceleration are still under development and important parameters, such as standard for lateral accelerations for ships with length less than 250 meters has yet to be defined. Still there are some observations that should be mentioned.

According to Annex 33 of [13], vulnerability criterion for excessive accelerations is to be applied for ships with length greater than 100 meters. However, as stated by delegation of Finland in Annex 21 of [13], calculation of level 1 vulnerability for small ships (L<100) leads to acceleration values that exceed the standard set by the criterion. These results are shown in Table 25.

Ballast Condition			Level 1			
			Option A		Option B	
Ship Type	LBP (m)	GM (m)	Achieved Value	Criterion Standard	Achieved Value	Criterion Standard
Dry Cargo	82	2.26	8.626	5.9	8.251	7.848
Supply Vessel	85	1.68	3.51	5.9	6.852	7.848
Supply Vessel	95	2.25	5.875	5.9	6.57	7.848

Table 25: Level 1 results from delegation of Finland [13]

Consequently, it is suggested to make vulnerability criteria for excessive accelerations applicable for all ships of length greater than 24m

Another troubling aspect of this criterion is the difference between the standard values for the two options ($5.9m/s^2$ for Option A and $7.848m/s^2$ for Option B). According to [24], which developed the method and equations used by the criterion, a standard for lateral acceleration should be set at 0.2g or $1.962m/s^2$. This value originates from statistical analysis of accidents related to loss of postural balance of sailors.

Risk Level	MII per min.	σ_{ay} / g	Sliding events per 3h
possible	0.1	0.081	0.0000
probable	0.5	0.099	0.0000
serious	1.5	0.123	0.0002
severe	3.0	0.150	0.0411
extreme	5.0	0.189	2.2573

Table 26: Risk levels (MII per minute), R.M.S. of lateral acceleration and sliding events per 3hours from [24]

However, the suggested standard by Annex 33 is greater in value and different for each option since it follows the guidance for container lashings where the maximum permissible lateral acceleration of containers is set to $0.8g=7.848m/s^2$ [35]. This makes it inconsistent with the work of [24] which is the basis of the criterion for excessive accelerations.

Last but not least, it should be mentioned that the calculation of the R.M.S. of lateral accelerations is based on a linear roll equation which includes Froude-Krylov wave excitation. On the other hand, important accelerations may occur during parametric rolling of significant amplitude as shown, for example, in [28], where values of 0.2g-0.3g are achieved for parametric roll amplitude of less than 25 degrees. Consequently, hazardous situations due to excessive lateral acceleration may occur during parametric rolling which are detected neither by parametric rolling nor by excessive accelerations criteria.

CHAPTER VIII

Future Work

Level 1 criteria of all forms of stability failure are simple and straightforward and thus, no further analysis should be required on their results. On the other hand, level 2 vulnerability checks and especially the ones for parametric rolling are in need of some further experimentation. The draft regulation for level 2B allows the calculation of vulnerability by various methods which, as shown in Chapter V.4 are inconsistent with each other. Proper testing of these methods could be carried out and compared against experimental results in order to determine which one is capable of simulating more accurately the phenomenon. Moreover, all level 2 regulations could be applied for vessels which had stability accidents in the past, in an effort to determine how consistent the regulations are with reality.

When level 2 vulnerability is detected, a third set of calculations will be needed, in the context of direct stability assessment. In the future, more methods and instructions regarding direct stability assessment will be suggested, utilising potential flow codes, computational fluid dynamics etc. The main issue with the use of these codes as a regulation, as stated in [20], is validation since different methods may produce different results for the same ship. Evaluation of these methods will be required in the future by applying them to a range of ships in order to detect the existence of inconsistencies or errors.

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APPENDIX A

Estimation of Linear and Cubic Roll Damping Coefficients

The following procedure is extracted from appendix 2 of Annex 17 of [13]:

The roll motion in calm water can be modelled as follows:

$$(I_{xx} + J_{xx})\ddot{\phi} + R(\dot{\phi}) + WGM\phi = 0 \tag{A.1}$$

Where I_{xx}+J_{xx}: virtual moment of inertia in roll

R: nonlinear roll damping

W: ship's displacement

If we introduce the equivalent linear damping coefficient, $B_{44}(\varphi_a)$, we obtain

$$(I_{xx} + J_{xx})\ddot{\phi} + B_{44}(\phi_a)\dot{\phi} + WGM\phi = 0 \tag{A.2}$$

Then,

$$\ddot{\phi} + 2\alpha_e\dot{\phi} + \omega_\phi^2\phi = 0 \tag{A.3}$$

Where $2\alpha = \dfrac{B_{44}(\phi_a)}{I_{xx} + J_{xx}}$ 、 $\omega_\phi = \sqrt{\dfrac{WGM}{I_{xx} + J_{xx}}}$.

On the other hand, the solution of Eq. (A.3) is given by $\phi = \phi_0 e^{-\alpha t}\cos(\omega_\phi t - \varepsilon)$ and the extinction curve is given by

$$\Delta\phi = a\phi_m + c\phi_m^3 = (a + c\phi_m^2)\phi_m = a_e\phi_m \tag{A.4}$$

Where $\Delta\varphi$: decrement of roll decay tests (radians) and φ_m: mean swing angle of roll decay test (radians). Thus,

$$a_e = \frac{\alpha T_\phi}{2} = \frac{\alpha\pi}{\omega_\phi} = \frac{B_{44}(\phi_a)}{2(I_{xx} + J_{xx})}\frac{\pi}{\omega_\phi} \tag{A.5}$$

Using the above relationship, a procedure to determine linear and cubic damping coefficients are as follows:

1) First, we obtain B_{44} with the roll amplitude, φ_a, of 1 degrees using Ikeda's simplified method. Using Eq. (A.5) and assuming $a=a_e$, we obtain the value of a.

2) Then, we obtain B_{44} with the roll amplitude of 20 degrees using Ikeda's simplified method. Using Eq. (A.5), we obtain the value of a_e.

3) Then, we determine c with the following equation and the value of a determined at the step

$$a_e = a + c\phi_m^2 \tag{A.7}$$

Where φ_m corresponds to 25 degrees.

4) Using the well-known energy relationship, linear and cubic roll damping coefficients can be calculated as follows:

$$\alpha = \frac{\omega_\phi}{\pi} a \tag{A.7}$$

$$\gamma = \frac{4c}{3\pi^2}\left(\frac{2\pi}{\omega_\phi}\right) \tag{A.8}$$

Please note B_{44} is normalised in Ikeda's simplified formula as follows:

$$\hat{B}_{44} = \frac{B_{44}}{\rho \nabla B^2}\sqrt{\frac{B}{2g}} \tag{A.9}$$

Where B: ship breadth

∇ : ship displacement volume

ρ : water density.