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THE IMPACT OF SHIPS STABILITY ON SAFETY OF NAVIGATION

ABSTRACT

of the thesis for obtaining the PhD degree

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Ship Handling and Navigation

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INTRODUCTION

In recent years, the number of accidents involving loss of ship stability was on the rise leading to damage of goods, loss of ships and lives. With the increasing of commodity transported and delivered to destinations as fast as possible, the speed of the ships increased which required major changes in ships design and construction in terms of deadweight capacity as well as hydrodynamic forms.

Presently are occurring modes of ship stability failure that a long period was treated only experimental. Moreover, a number of factors that in the past were only suppositions amplified the already known modes of ship stability failure.

If 25-30 years ago, at different international conferences, in the field of maritime transport, were presented general aspects related to ship stability failure modes, those were considered simple opinions about how the ship's intact stability could be affected, in different situations, from operational as well as environmental point of view. Practically, those opinions were treated with less importance to practical application. Moreover, there were no signs of encouragement from the competent authorities to implement the opinions in practice.

In the last ten years, intact ship stability loss has become a significant problem. Stability failure modes in severe sea conditions, large amplitude rolling generated by phenomena like parametric rolling, pure loss of stability broaching or surf-riding, appeared as a major problem especially with relevance to new ship designs, such as large container vessels. The starting point, which involved major claims of over $ 100 million, was the incident of container ship "APL China", and has proven that such phenomena exists beyond theory and can carry major risk for safety of ship and safety to navigation.

Although the theoretical existence of such dangerous phenomena has been known from before, the attention, from prevention and regulatory point of view, was paid only recently. Reality has proven that the mentioned casualty was not an isolated one and a number of vessels were involved in such situations, became a real danger for safety of navigation, with the result of loss the cargo and ship and potential risk for loss of lives.

The prediction of causes that lead to loss of intact stability and its impact on safety of navigation has attracted recently a huge interest documented in scientific publications and international conferences. In the same time, the subject has presented a significant interest of national and international regulatory authorities (Classification societies, International

Maritime Organization), because of the risks involved that could lead to loss of lives, cargo and ships.

The Classification Society American Bureau of Shipping was the first international authority that issued rules, in form of a guide, for assessment the ship's stability in order to prevent the occurrence of one of the most dangerous stability failure mode in extreme seas, like parametric rolling.

Despite the fact that the American Bureau of Shipping Guide is issued in a form of criteria used to determine if a particular vessel is vulnerable to parametric roll (susceptibility criteria) and how large the roll motions might be (severity criteria), the methodology of assessment is based on the calculations that are not accessible for ship's officers on board vessel. In order to be implemented as a practical tool, it is necessary a detailed computer software and thus is needed an additional cost for ships' owner. As a result, the assessment methodology remains for the moment just as guidance and more important with less applicability in practice.

Based on these observations can be considered that there is a necessity of rethinking the stability problems (arising from actual modes of ship stability loss) generating new requirements with the positive impact on safety of navigation that will protect lives, environment, and proprieties.

Considering the above statements, the principal idea underlying this approach can be described as follows: the instability events could be assumed as equal to the probability of encountering the critical situation that generate this instability and assessed from the beginning as a safety to navigation factor.

The opportunity of this thesis is given by the highlighting of some aspects that are insufficient approached in practical assessment of dynamic stability of ships in severe sea conditions as well as the demonstrated usefulness of theoretical and experimental approaches documented, analysed and proposed in the thesis.

The present work is important because is approaching the problem of assessment the ship's intact stability through the study of dynamic ship behaviour in severe sea conditions. The work is important not only from the theoretical point of view but also from practical point of view because it offers solutions for assessment of dynamic intact stability in a form of stability criteria (which presently is not covered by any regulations) that can be used on board vessels by ship's officers.

The main goal of the thesis is to develop a stability criterion for assessment the ship stability in waves, for parametric rolling and pure loss of stability, and to be implemented on board vessels as guidance for ship's officers. The current approach represents an attempt to fill the gap between the current stability regulations issued by IMO and the ship stability failure modes (like parametric rolling) which are presently not covered by these regulations. The approach is based on interfacing the deterministic analyses of dynamic ship stability with practicality on board vessel.

The study has relied on the following framework: basic loss of ship stability causes should be individually addressed where practical findings of the nature of this causes obtained by deterministic ship stability analyses and tools have to be exploited. Furthermore, the assessment should not focus on a single type of ship while appropriate casualties and statistics shall be incorporated in the procedure. Finally, the practicality has to be satisfactory.

The motivation for the idea driving this approach and the necessity to address in this thesis the issue of new approaching of assessment the ship stability comes from a number of observations from the field of ships stability losses and capsizing. Despite of the regulations in force, referring to intact ship stability, many ships continued to loss their intact stability and/or capsize.

The aim of the developed criteria is to help ship's officers to take an appropriate decision (avoid ship stability failure) based on the information derived from ship's characteristics, loading and environmental conditions for the intended voyage, prior commencement of the voyage. The proposed dynamic stability criteria developed in this thesis can be an advisory as well as a control tool of ship's behaviour in severe sea conditions.

Thesis objectives has been identified taking into account the necessity of rethinking the ship stability criteria for new stability failure modes in severe sea conditions as an issue of improving the safety of navigation in respect of ship stability. Thus, in the present thesis there are three main objectives proposed for study.

The first objective is to establish and analyze the causes and factors that affecting the intact ship stability in severe sea conditions.

The second objective is to develop a methodology for solving solution problems in respect of ship stability failure modes in severe sea conditions (for parametric rolling and pure loss of stability) in a form of dynamic stability criteria.

The third objective is to demonstrate the sufficient practicality of the developed criteria through applications (supported by various calculations and technical issues on an extended number of ships) and by implementation the modality of calculation on board ships.

Stimulated by the mentioned considerations, the thesis has been structured in 4 chapters. Firstly, a separate introductory chapter is presented which includes the relevance of the problem as well as the motivation. The final part includes the proposed objectives.

Chapter 1 aims to outline the importance of ship stability as a part of seaworthiness concept and the impact on safety of navigation. To have an image as close to reality about ship stability failure modes, a series of casualties involving loss of ship stability are presented, based on real case incidents, with emphasis on the factors and causes that are leading to such incidents. A detailed analysis of the ship stability failure modes in extreme sea conditions is provided, aiming to present how the ships face up the problem of stability loss.

The research carried out, introducing the subject of dynamic stability and reveals a number of possible dangerous situations encountered in heavy weather conditions (like parametric rolling, pure loss of stability, broaching and surf-riding) that currently are not covered by any regulations or guidance for preventing or avoiding such situations. In this respect, is outlined the present stability criteria, issued by International Maritime Organization, regarding the assessment of ship intact stability.

The synopsis of current stability criteria is illustrating the details at which stability requirements are determined, yet will also reveal the shortcomings of the criteria and the fact that the current stability criteria are not covering actual demand of safety for intact stability in certain situations. References of the present regulations are critically discussed and some conceptually approaches are proposed.

The main part of the thesis is focused on the development of a sustainable dynamic stability criterion for assessment ship's intact stability in waves.

In Chapter 2, is presented a detailed description of the proposed criteria for assessment ship stability in severe sea conditions, for parametric rolling and pure loss of stability, divided into a number of steps that forms the levels of vulnerability and susceptibility of ships for such phenomena.

Illustration of each level of stability criteria is presented, based on a mathematical model correlated with ship design characteristics and environmental conditions, aiming to reveal the structure of the new stability criteria proposed.

A new type of dynamic stability assessment criteria is developed by producing a diagram (risk map) that provides information about the stability condition of the ship based on actual loading condition and environmental factors.

The proposed assessment criteria takes the advantages that combines efficient tools and methods that can be easy accessed by officers on board ships.

Chapter 3 is devoted to implementation of proposed criteria in practice, through applicability for a large number of well-documented ships of different types, sizes and in different loading conditions. The aim is to demonstrate that certain categories of ships are vulnerable to dangerous phenomena in rough sea conditions, which are leading to loss of intact stability, and the proposed dynamic stability criteria can be a usefully computational tool for ship's officers that can give important information and guidance for avoiding such situations from the beginning of the voyage.

In Chapter 4 is proposed a procedure for implementaation on board ships of the methodology of assessment dynamic stability in waves for phenomena like parametric rolling and pure loss of stability.

The final part of the thesis is dedicated to general conclusions and personal contributions and indicates possible future research directions that can be continued, taken into consideration some situations and factors that were not considered in the present thesis.

The present work entitled "*The impact of ship's stability on safety of navigation*" is part of the works related to importance of ship stability assessment. It fits into a very complex system of research concerning the intact stability of ships, more exactly to modes of ship stability loss and the possibility of assessment the ship stability to prevent such losses.

CHAPTER 1

ACTUAL STAGE REGARDING SHIP'S STABILITY LOSS PROBLEMS AND THE IMPACT ON SAFETY OF NAVIGATION

A classical field of ship safety and safety to navigation is without any doubt the intact stability of the vessel. With regard to the safety of the vessel, the stability of a ship is of paramount concern.

Vessel's intact stability is a fundamental component of seaworthiness so it is in the interest of all owners, operators, charterers and naval architects to learn about this topic and ensure that their vessel possesses a satisfactory level of stability in order to ensure its safety as well as that of the people on board the ship. A basic principle to have the ship in a seaworthy condition is among other important things the understanding of ship's stability.

Like in any accident type, for the purpose to adopt the relevant safety measures and regulations to prevent such an accident in the future or to minimize the losses, in ship stability casualties it is essentially to keep a strictly statistic of those casualties. Hence, intact ship stability failure casualties have to be taken into consideration like separate events in the statistics. Moreover, the ship stability failure modes have to be identified and distinguished (between operational and environmental modes of stability loss) and the proper prevention measures have to be adopted.

A thorough study of research was undertaken on a number of 37 ships involved in casualties related to intact ship stability failure in severe sea conditions. Based on this study, it can be assumed that a ship may loose her stability or may capsize in at least four different ways:

- Pure loss of stability,
- Parametric rolling,
- Dead ship condition,
- Broaching and/or Surf-riding.

Pure loss of stability in waves

First mode of ship stability failure by physical phenomena is related to the variation of restoring lever in waves; the restoring moment becomes larger on the wave trough and smaller on the wave crest, thus, the result is the occurrence of very large roll angles under certain circumstances. The reason is the changes of ship's stability while the wave passing by. A possible scenario for the development of stability failure caused by pure loss of stability is presented in [23] and is illustrated below: First the ship sailing with relative high speed in following waves, figure 1.23, and a large wave is approaching from the stern. If the speed of the large wave is just slightly above the ship speed, the time duration for the large wave to pass the ship may be long. There is a typical changes of stability caused by relative small waves (fig. 1.24).

Fig.1.23 Vessel sailing in following waves, large wave approaching from stern

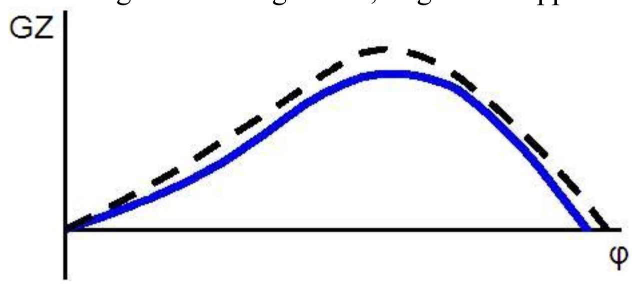

Fig.1.24 Changes of stability caused by small relative waves

Then, the large wave is overtaking the ship (fig. 1.25). Once the crest of the large wave is near the midship section of the ship and if the time exposure to the crest of the large wave is long enough, the stability may be significantly decreased.

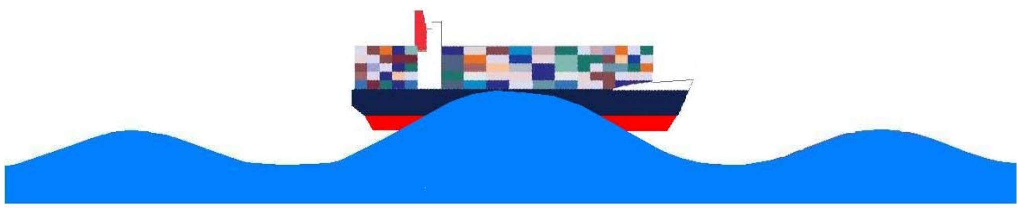

Fig.1.25 Large wave is overtaking the ship

In this situation there is a large decrease of the instantaneous GZ curve, caused by the crest of the large wave (fig. 1.26).

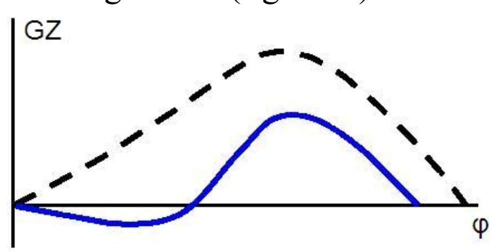

Fig.1.26 Decrease of stability caused by the wave crest

Because the wave speed is just slightly more than ship speed, the condition of decreased stability may exist long enough for the ship to develop large heel angle, or even capsize.

As the large wave has passed the ship (fig. 1.27), her stability is regained and the ship will eventually return to the upright position, if she did not already heel too far. Otherwise, typical changes of stability, caused by relatively small waves, are encountered.

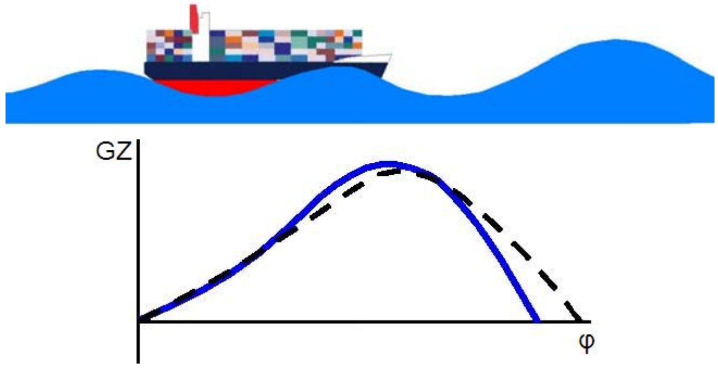

Fig.1.27: Large wave passed over the ship and the stability is regained

Parametric rolling

Parametric roll behavior may lead to sudden increase in large roll amplitude angles experienced by the ship typically in longitudinal waves, caused by parametric roll resonance (the encounter frequency of waves of length similar or larger than the ships length is comparable to twice the ship's roll natural frequency) [6].

Periodic stability variations, occurring with certain frequency (about twice the roll frequency) are the cause of development the parametric rolling. This was very well explained in [23] and is illustrated in figure 1.32.

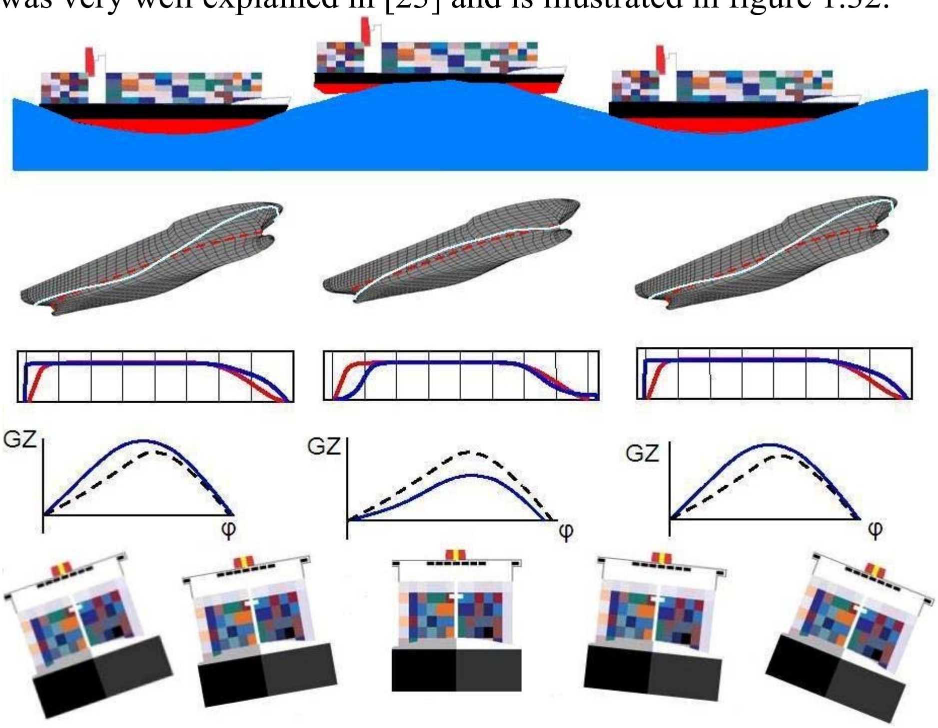

Fig.1.32 Developing of parametric roll [23]

If the ship is rolled on the wave trough, due to a wide waterline, the restoring moment is increased over its magnitude in still water. If the wave crest is amidship at that time, due to the greater speed of rolling and less resistance of heeling, the stability is decreased and the ship will roll further the opposite side.

Finally, the vessel comes again with midship section on the wave trough, where the stability is again large. This situation leads to a large push back force and the ship roll more over (because the roll speed was increased in previous step) which leads to a larger roll angle and the ship reaches its maximum amplitude roll. The scenarios repeats until the ship capsize or stabilize up to a certain roll angle.

Analysis of actual intact ship stability criteria

The General Stability Criteria reveals that the regulations are still based on the same assumptions, according to which the ship indicator of stability safety is the righting arm curve on calm water.

The assumed Weather Criterion is simply to use, it is based on physical phenomena / modeling but was adjusted with capsizing casualties in the form of the wind velocity. In other words, the wind velocity in the weather criteria does not represent the actual sea state and has rather empirical meanings. In fact, it concerns only one mode of ships loss and the level of safety is largely unknown.

Although it considers the dynamics of ship roll motions, at least in a simplified way, this prescriptive scenario is not suitable to assess phenomena endangering ships in head, following and quartering waves and it also never was intended to be used in such a way [89]. The safety level guaranteed to the ships by the compliance with stability criteria, however, is in general unknown and it is still a big open problem. From the point of view of ship's safety this is however, not the final solution. The evidence is given by the stability casualties that continue to occur despite the fact the those ships meets the existing IMO stability criteria.

Conclusions

1. Ships stability is a very important component of seaworthiness concept.
2. Loss of ship stability has a great share and is an important cause of the maritime casualties with a huge impact on safety of navigation, being a serious threat in this respect.
3. Any loss of intact stability, due to one of the causes presented in this chapter, will lead to a dangerous situation that will directly affect the safety of navigation.

4. Present stability regulation are not covering the stability failure modes in severe sea conditions (like parametric rolling).

Based on the studies and analysis presented in this chapter the following tasks have to be settled:

1. The necessity of establishing a new set of stability criteria, to show the vulnerability and behavior of the vessels in severe sea conditions
2. The validation of the stability criteria through calculations on various types of ships
3. The implementation on board vessel of the procedure for calculation the dynamic stability as a useful and accessible computational tool for ship's officers

In this respect, one of the main tasks of the thesis is to cover this goal: to develop a method of assessment the intact stability of ships, in a form of dynamic criteria, to cover the phenomena like pure loss of stability and parametric rolling.

CHAPTER 2

THE CONCEPT AND METHODOLOGY OF THE PROPOSED DYNAMIC STABILITY CRITERIA

The scope and the principle of the proposed dynamic intact stability criteria

The scope of the proposed dynamic intact stability criteria in this thesis is:

- To provide methods to assess particular intact stability failure modes for ships in severe sea conditions.
- To ensure that the minimum initial value of GM in calm water, obtained for a specific vessel with a specific hull form, is enough to balances the crest-trough variation in a particular condition of wave.

The structure of the proposed dynamic intact stability criteria

The suggested intact stability criteria, presented in figure 2.2, is designed to have a multi-level structure, based on empirical approach and it has the basis in the simplified determination of stability factors that may be judged quantitatively in the end.

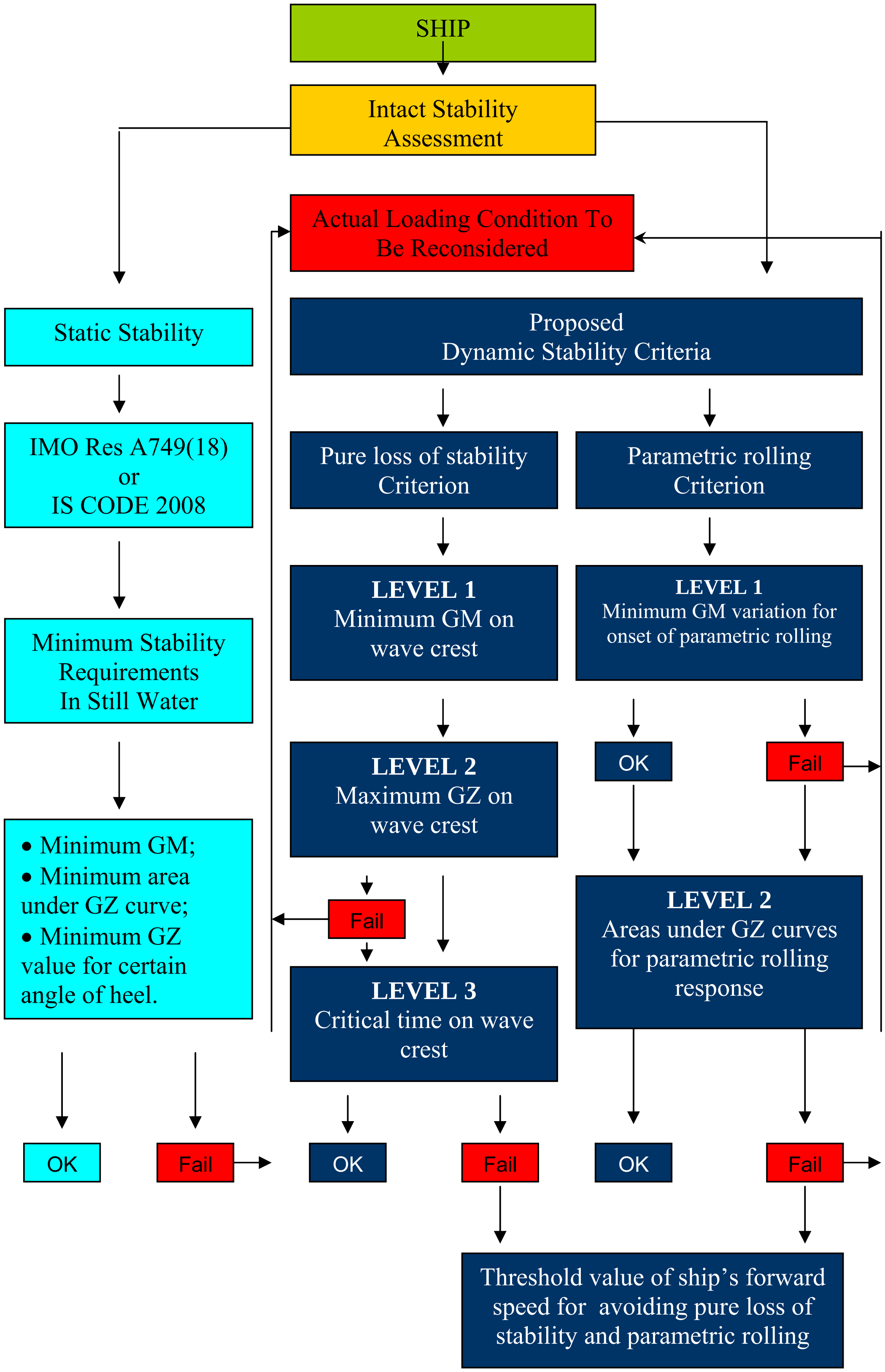

Fig.2.2 Structure of the proposed dynamic intact stability criteria

The calculation procedure of the proposed dynamic intact stability criteria

Modeling of environmental conditions

In order to be assessed the ship's susceptibility to pure loss of stability and parametric rolling in longitudinal waves it is necessary to be established the environmental conditions and especially the parameters of waves encountered.

The conventional or standard wave, which is taken into consideration for proposed dynamic intact stability criteria has the trohoidal profile because, has the closest profile of the wave that is encountered in reality due to wind action.

Based on [49], another set of environmental conditions can be designed, where a deterministic relation between the wave spectral period T_w [s], wind speed U [m/s] and the significant wave height H_w [m] is provided.

If a regression of data is used from [49], then the following relations, between the above three parameters, are obtained:

$$H_w = 0.07915 \cdot U^{1.5} \tag{2.1}$$

$$U^{0.75} = 0.97728 \cdot T_w \tag{2.2}$$

If the eq. (2.1) and (2.2) are combined, then the following relation for the wave height is obtained

$$H_w = 0.07560 \cdot {T_w}^2 \tag{2.3}$$

The relation that ascertain the wave period in correlation with the wavelength is

$$T_W = \sqrt{\frac{2\pi\lambda}{g}} = 0.8\sqrt{\lambda} \tag{2.4}$$

Thus, from the eq. (2.3) and (2.4) is obtained a relation of wave height based on wavelength as

$$H_w = 0.04838 \cdot \lambda \tag{2.5}$$

The equation (2.1) can be compared with the values of wave height calculated from the values of wind speed provided from the Beaufort Scale, as in table 2.2

Table 2.2 Correlation between wind speed and wave height as per Beaufort Scale

Beaufort Scale	4	5	6	7	8	9	10	11	12
Wind speed U , m/s	5.5-7.9	8.0-10.7	10.8-13.8	13.9-17.1	17.2-20.7	20.8-24.4	24.5-28.4	28.5-32.6	>32.8
Wave height H_w, m	1-2	2-3	3-4	4-5.5	5.5-7.5	7-10	9-12.5	11.5-16	>14

In this way, based on the equations (2.1) and (2.5) and the values of wave height from the table 2.2, we can assume, for our proposed stability criteria, the following deterministic values of the wave height in correlation with the wavelength as per table 2.3.

Table 2.3 Assumed relation between wave length and average wave height

Wave length λ, m	50	100	150	200	250	300	350
Wave height H_w, m	2.5	4.8	7.25	9.7	12.1	14.5	16.9

For intermediate wave lengths, linear interpolation my be used. However, the large values of wave heights will be limited by the condition $H_w \leq D - d_m$, where D is the ship's depth and d_m is the ship's mean draft.

Stability criterion for parametric rolling

The proposed methodology for the assessment of parametric rolling in waves is based on the following levels (fig.2.5):

1. Assessment of minimum GM variation for onset of parametric rolling,
2. Assessment of areas under GZ curves for parametric rolling response,
3. Establish a threshold value for ship's forward speed, in order to avoid the parametric rolling phenomenon

Minimum value of GM variation for onset of parametric rolling

The calculation of assumed waterlines, based on the considered wave height is modeled as follows:

- When the wave crest is situated amidship, the waterline is considered a straight line for the lowest draft, lower waterline – LWL (fig. 2.6).

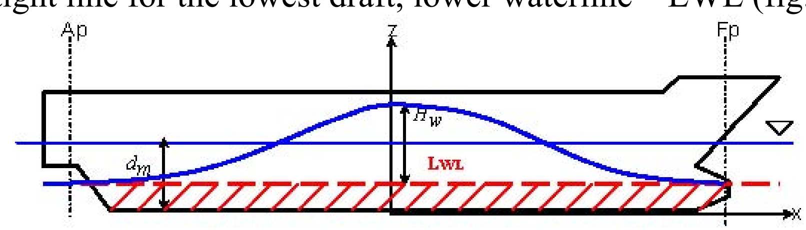

Fig.2.6 Considered lower water line – LWL - for wave crest amidship

- When the wave trough is situated amidship, the waterline is considered a straight line for the highest draft (upper waterline – UWL), at a vertical distance defined as the height of the wave, measured from the lower waterline (fig. 2.7).

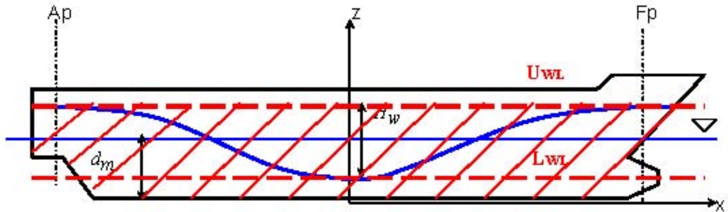

Fig.2.7 Considered upper water line – UWL - for wave trough amidship

The above-described simplified way of calculation, is based on the idea that waterplane variation amidships has less influence on stability changes, considering the

The draft for lower and upper waterline is calculated from the relation (2.20), which is a combination between ABS relation used in [3], wave relation obtained from [166] and quotations from figure 2.9, as follows:

$$d_{(x_c,x_i)} = d_m - x_F \tan\theta \pm 0.5 \cdot H_w \cdot \cos\frac{2\pi(x_i - x_c)}{\lambda}$$

(2.20)

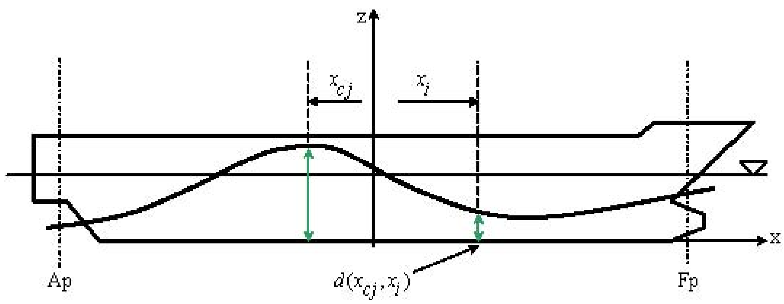

Fig. 2.9 Definition of draft in relation with position of wave crest

For our proposed model of stability criteria we considered the wave crest is exactly at midship position, where $x_i = x_c$, and the vessel is considered in a even keel situation (which means that angle of longitudinal inclination is zero) thereafter the formula for the draft at upper and lower waterline will become

$$d_{U,L} = d_m \pm 0.5 \cdot H_w. \qquad (2.21)$$

Thus, the metacentric height, for upper and lower waterline considered, can be easily calculated from the relation

$$GM_{U,L} = BM_{U,L} - KG + VCB_{U,L}. \qquad (2.22)$$

Thereafter, the variation of metacentric height can be determined as

$$\delta GM = \frac{GM_U - GM_L}{2}. \tag{2.23}$$

The equation of ship rolling in longitudinal waves can be considered in a way presented by Francescutto in [46], as

$$I_x \ddot{\varphi} + D(\dot{\varphi}, \varphi) + R(\varphi, t) = 0. \tag{2.24}$$

If the onset of parametric rolling is considered at $\varphi(t) = 0$, in the situation of restriction for the moment to analysis of stability, the problem is simplified and the equation (2.24) can be written in a linearised form as

$$I_x(\ddot{\varphi}) + D\dot{\varphi} + \Delta\overline{GM}(t)\varphi = 0. \tag{2.25}$$

If it is considered that the variation of transversal metacentric height is in a sinusoidal form, then the equation (2.25) becomes a Mathieu type equation as follows

$$\ddot{\varphi} + 2\eta\dot{\varphi} + \omega_\varphi^2 \left[1 + \frac{\delta GM}{GM_0} \cos(\omega_E t) \right] \varphi = 0, \tag{2.26}$$

which is a differential equation with periodic coefficients and its solution are solved through Floquet theory.

Since the occurrence of parametric rolling is fully dependent by the conditions for wave encounter frequency, large variations of metacentric height and sufficiently low damping, a threshold value for the onset of parametric rolling is obtained from equation (2.26) in a reduced form as

$$2 - \frac{1}{2}\left(\frac{\omega_E}{\omega_\varphi}\right)^2 < \frac{\delta GM}{GM_0} < \frac{1}{2}\left(\frac{\omega_E}{\omega_\varphi}\right)^2 - 2, \tag{2.27}$$

which reveals a minimum threshold value in the proximity of the condition $\omega_e = 2\omega_\varphi$ that can be written as

$$\frac{\delta GM}{GM_0} = \frac{4\eta}{\omega_\varphi}, \tag{2.28}$$

where, η is the total roll damping coefficient, ω_φ is the ship natural roll frequency and GM_0 is the metacentric height for draught corresponding to actual ship loading condition.

The eq. (2.28) expresses the fact that stability variation is sufficient to induce parametric rolling. The chances for development of parametric rolling are high when the ratio is large, then the threshold can be expressed as the critical minimal value of $\frac{\delta GM}{GM_0}$ for which large resonance occurs, as

$$\frac{\delta GM}{GM_0} > \frac{4\eta}{\omega_\varphi}. \tag{2.29}$$

In ship's roll motion, damping is of particular attention and should be calculated as accurately as possible. An empirical form, for the assessment of the total roll damping coefficient, can be applied from the model test of Miller as described in [115]**.** Through this method, it is calculated the total damping in roll motion as a sum of two components (the linear and non-linear damping roll) as follows

$$\eta = \eta_1 + \eta_2 \cdot \sqrt{\varphi_a} \;, \tag{2.30}$$

where:

$$\eta_1 = C_v \cdot 0.00085 \cdot \frac{L}{B} \cdot \sqrt{\frac{L}{GM_0}} \cdot \left[\left(\frac{F_n}{C_b} \right) + \left(\frac{F_n}{C_b} \right)^2 + 2 \cdot \left(\frac{F_n}{C_b} \right)^3 \right], \tag{2.31}$$

$$\eta_2 = 19.25 \cdot \left(A_{bk} \cdot \sqrt{\frac{l_{bk}}{r_b}} + 0.0024 \cdot L \cdot B \right) \cdot \frac{r_b^3}{L \cdot B^3 \cdot d \cdot C_b}. \tag{2.32}$$

in which:

A_{bk} - one sided area of bilge keel (m²)
l_{bk} - length of bilge keel (m)
h_{bk} - height of bilge keel (m)
r_{bk} - distance center line of water plane to turn of bilge (m)
(first point at which turn of bilge starts, relative to water plane)
L - length of ship (m)
B - breadth of ship (m)
d - draft of ship (m)
C_b - block coefficient
F_n - Froude number, ($v/\sqrt{gL}$)
φ_a - amplitude of roll (radians)
C_v - correction factor for speed, generally is 1.

The minimum areas under righting moment curves for parametric rolling response

Based on the relationship between damping coefficient and ratio of areas under righting moment curves for wave crest and wave trough amidship, the potential risk regions of parametric roll motions can be determined.

For a ship running in longitudinal seas, an equation of motion may be described in the following form, as written by Bullian in [30]:

$$(I_x + J_x)\ddot{\varphi} + D(\dot{\varphi}) + \Delta \cdot GZ(\varphi, t) = 0, \tag{2.33}$$

where, $(I_x + J_x)$ are the real and added moments of inertia, $D(\dot{\varphi})$ is the damping force, Δ is the ship displacement and $GZ(\varphi, t)$ is the righting arm.

If in the equation (2.33) are considered the damping coefficient, the ship's natural roll frequency and the metacentric height, it can be written as

$$\ddot{\varphi} + 2\eta\dot{\varphi} + \omega_\varphi^2 f(\varphi, t) = 0, \tag{2.34}$$

where, η is coefficient of roll damping, ω_φ is the natural roll frequency and $f(\varphi, t)$ is the time dependent stiffness.

Therefore, the areas under GZ curves for wave crest and wave trough condition are calculated as follows:

$$A_{crest} = \int_0^\varphi GZ_{L_{WL}}(\varphi) d\varphi, \tag{2.36}$$

$$A_{trough} = \int_0^\varphi GZ_{U_{WL}}(\varphi) d\varphi. \tag{2.37}$$

The modeling of the GZ it is important because it reveals the amplitude of roll motion. It was assumed that the metacentric height on waves has a sinusoidal variation given by the relation

$$GM_{wave} = GM_0(\alpha_1 + \alpha_2 \cos \omega_e t), \tag{2.40}$$

where,

$$\alpha_1 = \frac{GM_{L_{WL}} + GM_{U_{WL}}}{2 \cdot GM_0}, \text{ is the average variation of GM,} \tag{2.41}$$

$$\alpha_2 = \frac{GM_{U_{WL}} - GM_{L_{WL}}}{2 \cdot GM_0}, \text{ is the amplitude of wave-induced variation in GM.}$$

Thus, the righting arm could be written in a linearised form as

$$GZ(\varphi, t) = GM_0(\alpha_1 + \alpha_2 \cos \omega_e t)\varphi. \tag{2.43}$$

In longitudinal waves, the frequency of ship rolling is almost the same with the natural frequency, and the relation that can approximate the rolling angle is based on Hamamoto [54], as

$$\varphi(t)=\xi_1\cos\omega_\varphi t+\xi_2\sin\omega_\varphi t\,. \tag{2.44}$$

In order to find the encounter frequency that leads to parametric rolling it will be applied the energy balance method in eq. (2.34) as follows

$$\int_0^T \ddot{\varphi}d\varphi+\eta\int_0^T \dot{\varphi}d\varphi+\omega_\varphi^2\cdot\alpha_1\int_0^T \varphi d\varphi+\omega_\varphi^2\cdot\alpha_2\int_0^T \varphi\cos(\omega_E t)d\varphi=0. \tag{2.45}$$

By substituting the derivatives of equation (2.44) into equation (2.45) is obtained the following

$$\eta\cdot\omega_\varphi^2(\xi_1^2+\xi_2^2)\cdot T+\alpha_2\cdot\omega_\varphi^3\int_0^T\left[\xi_1\cdot\xi_2\cos 2\omega_\varphi t-\frac{1}{2}(\xi_1^2-\xi_2^2)\sin 2\omega_\varphi t\right]\cos(\omega_E t)dt=0. \tag{2.46}$$

In order to occur the parametric rolling, it is necessary to be fulfilled the condition that the encounter frequency should be equal to twice the natural rolling frequency.

In the same time, the equation (2.44) can be rewritten as

$$\varphi(t)=\varphi_{cr}\cos(\omega_\varphi t-\gamma)\,, \tag{2.47}$$

where, φ_0 is the critical roll angle given by the relation

$$\varphi_{cr}=\sqrt{\xi_1^2+\xi_2^2}\ \text{ and }\ \gamma=\tan^{-1}\left(\frac{\xi_1}{\xi_2}\right). \tag{2.48}$$

Then, from the equations (2.46) and (2.47), ξ_1 and ξ_2 are determined in a form of equations that describe the critical condition where constant rolling amplitude is maintained.

$$\xi_1^2=\frac{\varphi_{cr}^2}{2}\left[1+\left(\frac{2\eta T_\varphi}{\pi\alpha_2}\right)\sin\omega_\varphi\pm\sqrt{1-\left(\frac{2\eta T_\varphi}{\pi\alpha_2}\right)^2}\cos\omega_\varphi\right] \tag{2.49}$$

$$\xi_2^2=\frac{\varphi_{cr}^2}{2}\left[1-\left(\frac{2\eta T_\varphi}{\pi\alpha_2}\right)\sin\omega_\varphi\mp\sqrt{1-\left(\frac{2\eta T_\varphi}{\pi\alpha_2}\right)^2}\cos\omega_\varphi\right] \tag{2.50}$$

The risk and no risk zones can be determined from the behaviour of ξ_1 and ξ_2 which have to be considered as a function of time (in order that the rolling angle to increase up to a risky zone and decrease to a no risk zone) as follows

$$\varphi(t)=\xi_1(t)\cos\omega_\varphi t+\xi_2(t)\sin\omega_\varphi t\,. \tag{2.51}$$

The risk zones for parametric rolling is specified by the factor

$$(\varepsilon+\eta)^4+2(2\omega_\varphi^2+\alpha_1\omega_\varphi^2-\eta^2)(\varepsilon+\eta)^2+\omega_\varphi^4\left(\alpha_1^2-\frac{\alpha_2^2}{4}\right)-2\alpha_1\eta\omega_\varphi^2+\eta^4=0 \quad (2.55)$$

Based on the value of ε from equation (2.55) is determined the rolling motion as follows:

- If $\varepsilon > 0$, rolling motion increases;
- If $\varepsilon < 0$, rolling motion decreases;
- If $\varepsilon = 0$, rolling motion is critical.

Thus, it can be expressed the condition that leading to capsize, in longitudinal waves, as follows

- $\eta < \frac{\pi}{2}\left(\frac{\alpha_2-\alpha_1}{T}\right)$ in a capsizing zone, (2.56)
- $\eta = \frac{\pi}{2}\left(\frac{\alpha_2-\alpha_1}{T}\right)$ in a risk zone, (2.57)
- $\eta > \frac{\pi}{2}\left(\frac{\alpha_2-\alpha_1}{T}\right)$ in a risk free zone. (2.58)

In this way, by fitting the results with first-degree polynomials, the risk zones for parametric rolling may be defined in connection with the area ratio and damping coefficient as per figure 2.12.

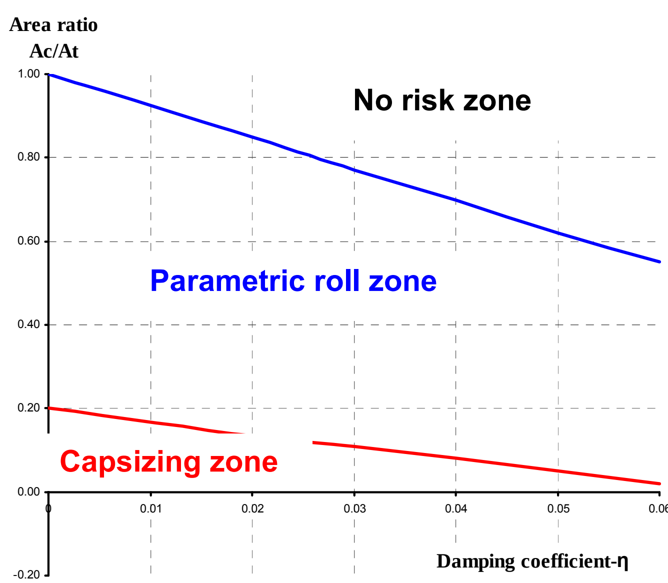

Fig. 2.12 Potential capsizing and parametric rolling zones related to area ratio and damping coefficient.

The equations for damping coefficients were defined for risk zones as a function of area ratio as follows:

- $\eta > -0.0814\dfrac{A_{crest}}{A_{trough}} + 0.0924$, risk free zone; (2.60)
- $\left\{\begin{matrix} \eta < -0.0814\dfrac{A_{crest}}{A_{trough}} + 0.0924 \\ \eta > -0.0870\dfrac{A_{crest}}{A_{trough}} + 0.0675 \end{matrix}\right\}$, parametric roll zone; (2.61)
- $\eta < -0.0870\dfrac{A_{crest}}{A_{trough}} + 0.0675$, capsizing zone. (2.62)

The threshold value of ship's forward speed for susceptibility to parametric rolling

The encounter period of longitudinal waves (in head and following seas) is given by the equation,

$$T_E = \frac{1}{\dfrac{1}{T_w} - \dfrac{2\pi}{g} \cdot \dfrac{V_S}{T_w^2} \cdot \cos\alpha}. \qquad (2.66)$$

For the condition of parametric roll, the relation that gives the ship's speed in longitudinal waves is,

$$V_{pr} = \frac{g}{2\pi}(T_W - \varepsilon\frac{T_w^2}{T_\varphi}), \text{ for head waves and } 1.8 < \varepsilon < 2.0, \qquad (2.69)$$

or,

$$V_{pr} = \frac{g}{2\pi}(\varepsilon\frac{T_w^2}{T_\varphi} - T_w), \text{ for following waves and } 2.0 < \varepsilon < 2.1, \qquad (2.70)$$

The ship susceptibility for parametric roll development shall be calculated for the speed range as per relations (2.69) and (2.70) and taking into consideration the condition that wave length to be equal with ship's length. If the ship's speed does not take the values defined by the relations (2.69) and (2.70) then the ship is not susceptible to parametric roll and a further check is not necessary. Thus, in order to avoid parametric rolling the actual ship's speed have to be:

$$V_{s\max} > V_{pr}, \qquad (2.75)$$

where, $V_{s\max}$ is the maximum speed of the ship that can be developed in extreme seas.

Stability criterion for pure loss of stability

The assessment criteria considers the main following aspects:

- Ship actual loading condition, from where can be deducted the critical KG that leads to critical GM and maximum positive value of GZ on the wave crest.
- The time expected to be spent by the ship on the wave crest during possible large inclination of ship can be developed and thus pure loss of stability phenomenon appears.

Assessment of minimum GM on wave crest

The calculation of GM on the wave crest, is based on the same simple mode of assessment as used for parametric rolling, considering that when the wave crest is amidship, the waterline is a straight line for the lowest draft at a vertical distance equal with half of the mean draft, as represented in figure 2.17.

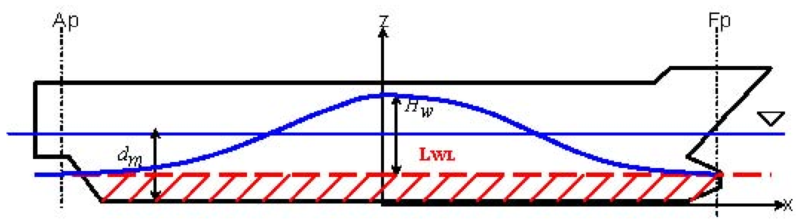

Fig. 2.17 Considered lower water line – LWL - for wave crest amidship

Thus, the metacentric height for the lower waterline considered, which is the metacentric height on the wave crest, is calculated with the relation

$$GM_{x_C} = BM_L - KG + VCB_L . \qquad (2.77)$$

The figure 2.18 illustrates the values of GM as a function of the wave crest along the ship's hull.

The value of $GM(x_c)$ is the minimum value, $GM_{\min}$, that the ship can encounter on waves and thus, the first level of stability assessment for pure loss of stability in waves is that GM on the wave crest to be positive

$$GM(x_c) > 0 . \qquad (2.78)$$

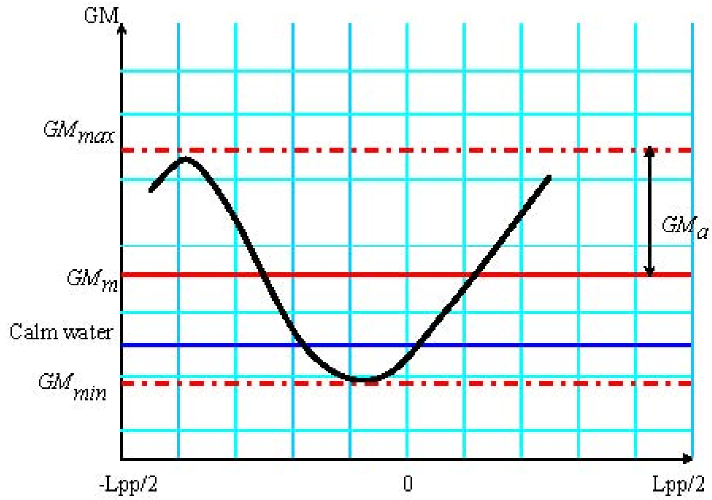

Fig. 2.18: Illustration of GM curve as a function of wave crest position

Based on this fact we can assume that if this value is negative the ship is susceptible to develop a potential danger for pure loss of stability.

Assessment of maximum GZ in waves

In our proposed criterion, the vessel was assumed "stuck" on the wave crest. This situation can be considered similar to a static condition (the vessel is statically balanced on the free surface) and then the righting lever may be calculated as transient GZ at that moment and can be modeled, by using of GZ curve in calm water, as:

$$GZ_{x_c}(\varphi) = GZ_0(\varphi) - (GM_0 - GM_{x_c})\sin(\varphi). \tag{2.79}$$

At this level, the value of the calculated $GZ_{\max}$ need to be positive in order that the ship not to be vulnerable to pure loss of stability, thus

$$GZ_{\max} > 0. \tag{2.80}$$

If the calculated $GZ_{\max}$ is negative then this criterion supports the conclusion of previous criterion of $GM_{\min}$ and ship fails to comply being possible to be vulnerable to pure loss of stability especially if spend enough longer duration on the wave crest.

Assessment of the critical period spent by the ship on the wave crest

This proposed criterion is a extended model of the method presented in [140], based on the correlation between the time spent by the ship on the wave crest with the time that it takes to reach a large angle of heel. In the proposed criterion, the time spend on the wave crest is used as a ratio with the natural roll period of ship as an indication of the possibility to develop large angles of heel.

The time spent by the ship on the wave crest, during the GM is negative, is represented in figure 2.19.

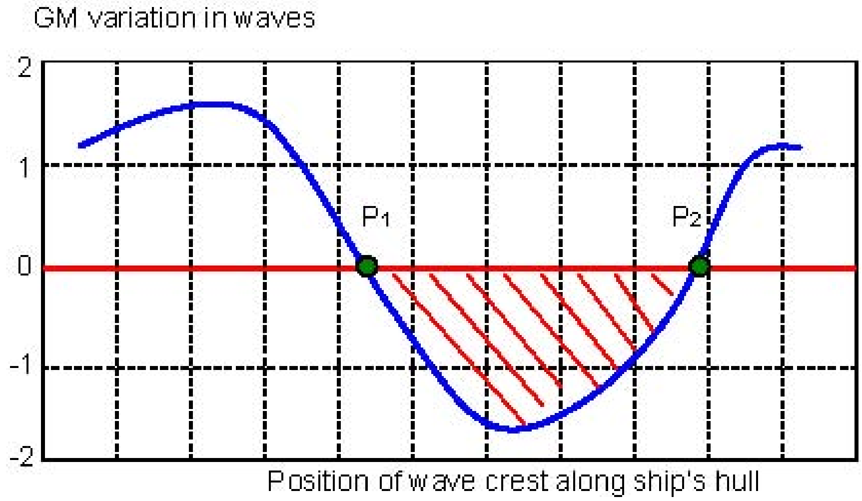

Fig. 2.19 The duration spent on wave crest with negative GM

The positions P1 and P2 is indicating the interval of time when the GM remains negative while the ship is on the wave crest, based on the same consideration such as used in IS Code 2008 [76].

This interval can be expressed as

$$t(x_c) = \frac{P_2 - P_1}{c_w - V_s}, \tag{2.93}$$

where, V_{ship} is the ship's speed and c_w is the wave celerity calculated from the relation

$$c_w = \frac{\lambda}{T_w} = \sqrt{\frac{g}{2\pi} \cdot \lambda} = \sqrt{1.56 \cdot \lambda} = 1.25 \cdot \sqrt{\lambda}\ . \tag{2.94}$$

The distance $(P_2 - P_1)$ may calculated as a fraction of ship's length and may be considered as follows:

- For the actual design of containers ships, the flared portions in fore and aft parts of the hull are extended at almost 1/4 from length. In this respect, the fraction of ship length considered for the proposed criteria is about half of ship's length, figure 2.20.

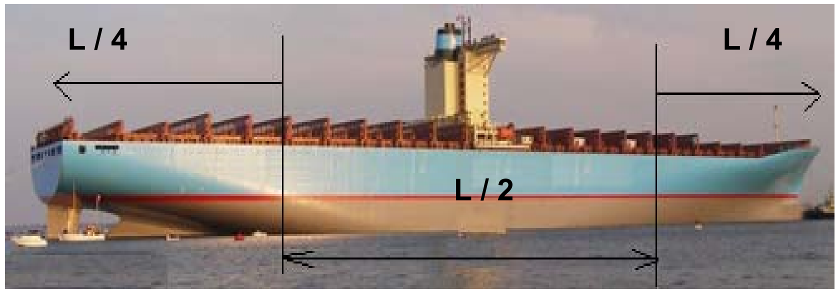

Fig. 2.20 Fractions of the ship's length, container ship

- For the actual design of car carrier ships, the flared portions in fore part of the hull is extended at about L/3 from length, whilst in aft part of the hull to about L/4 from length. In this respect, the fraction of ship length considered for the proposed criteria is about 0.416 from ship's length, figure 3.21.

Fig. 2.21 Fractions of the ship's length, car carrier ship

If $t(x_c)$ represents a short duration, then the stability will be reduced below zero, only for a short period, and this fact may not be significant. In case of longer duration of reduced stability below zero, large roll angles may be developed, leading to a dangerous loss of stability or even to capsize. Based on the $t(x_c)$ and the ship natural roll period, is defined the ratio $\frac{t(x_c)}{T_\varphi} \geq 1$,which can be used as a possible criterion for indicating the possibility of the ship to develop large roll angles or even capsize during decreasing of GM to negative values.

The meaning is if this ratio is small, the ship is not susceptible for pure loss of stability but in the same way, if the ratio is large, approaching to 1, the ship may have time to develop large rolling angles and to loss stability due to decrease of GM for a long duration.

Conclusions

In the present chapter was presented a proposed dynamic stability criterion for the assessment of ship instabilities in waves due to phenomena like pure loss of stability and parametric rolling. The criterion was developed taken into consideration the main factors that affect the dynamic stability, i.e. the waves and the characteristics of the ships (loading conditions as well as hydrostatic particulars).

The proposed criteria is developed in a multi-level scenario. Each level, give the possibility of assessment the vulnerability of ships to dynamic instabilities and the possibility to take corrective actions in order to avoid, from the beginning of the voyage, the exposure of ships to dangerous phenomena in severe sea conditions.

The first level of the criteria is based on the assessment of minimum metacentric height (the first indicator of ship's stability) when the wave crest is amidships (the most dangerous situation). Thus, the intention of this level is to find out how much should be the minimum metacentric height in order to be sufficient against loss of stability in this situation.

As only the value of metacentric height is not revealing all the times the vulnerability of ships to dangerous phenomena in waves, the second level of stability criteria is applied. This level is based on the calculation and assessment of the righting level because it determines the capacity of ships to regain the stability as well as the amplitude of roll motion.

In the final level, the time spend by the ship on the wave crest is used as a ratio with the natural roll period of ship for indication the possibility to develop large angle of inclination. The scope of this level is to provide informations regarding the duration that the stability of ship is below negative values as well as the values of vessel's speed that have to be established in order to spend less time below negative metacentric height. Thus, if the vessel fails to comply with the level 1 and level 2, the criteria give the possibility to take measures, for avoiding such dangerous situations in severe seas, by establishing threshold values of vessel's speed calculated basis on actual loading condition, ship's dimensions and hydrostatic particulars.

CHAPTER 3

VALIDATION OF THE PROPOSED DYNAMIC STABILITY CRITERIA

Validation of the proposed dynamic stability criteria for an extended number of ships in full loaded condition

In order to show the sustainability of the proposed dynamic stability criteria for the assessment of parametric rolling and pure loss of stability, the sample calculations were extended for a number of 34 ships of different types and sizes.

Sample calculation for assessment of parametric rolling

Sample calculations, for assessment of parametric rolling, were performed following the methodology of assessment the minimum value of GM variation for onset of parametric rolling and calculation of minimum areas under righting moment curves for parametric rolling response, described in the proposed stability criteria. The results are illustrated in the Annex III.

The categories and number of ships that failed to comply with Level 1 and Level 2 criterion for parametric rolling are illustrated in Annex IV.

Sample calculation for assessment of pure loss of stability

Sample calculations for assessment of pure loss of stability were performed following the methodology of calculation the minimum GM on the wave crest, the maximum GZ in waves and the critical period spent on the wave crest, described in the proposed stability criteria. The results are illustrated in the Annex V.

The categories and number of ships that failed to comply with Level 1 criterion for pure loss of stability are illustrated in Annex VI.

For the Level 2 of pure loss of stability criterion, all the ships used for sample calculations passed the restriction of $GZ_{\max} > 0$. It is important to be noted, that even the categories of ships that failed to pass the first level of criterion complied with the second level. This is because, despite the fact that initial metacentric height has negative value, the ships spent less time on the wave crest and the time of loss of stability becomes small.

The development of a faster partial stability failure, as the upright equilibrium is no longer stable, may be the consequence of appearance of an angle of loll. In case of negative stability for large roll angles (even up to 30 degrees) in a wave crest situation a ship can stay in a stable condition, with a constant heel, but only in a static situation. Because of the dynamic behaviour of the sea, the roll energy is slowly dissipated and the ship can experience negative stability on group of wave crests in a row, which results in excessive rolling over 30 degrees.

However, if the maximum roll angle exceeds large values the danger of occurring large accelerations is high. The result can be the collapse of cargo stows and breaking of lashings, which can lead to capsize of the ship.

It can be concluded that the values obtained in the level 1 criterion are much smaller that from direct calculation and in this case the level 1 criterion can be considered more conservative than the level 2 criterion.

Conclusions

Comparing the sample calculation results for assessment of parametric rolling and pure loss of stability it can be observed that there is a great distinction between categories of ships.

The proposed criteria divides the sample ships used for calculation in two distinctive groups as follows:

- In the first group are ships like oil tankers, gas carriers, multipurpose ships and bulk carriers, that complies with the level 1 and level 2 criterion for parametric rolling and pure loss of stability, and can be considered conventional ships, not at risk for failures related to stability changes (righting lever variations) in waves.

This group of ships passed the criteria mainly due to geometry of hull, because these types of ships have only small bow flares (in case of gas carriers or multipurpose ships) or have almost wall sided bow (in case of bulk carriers or oil tankers) as shown in figures 3.45.

- In the second group are ships like container ships, Ro-Ro ships or Pure Car Carrier ships, which not pass the levels of criteria, and can be considered with a high risk for stability failures related to righting arm variations in waves.

This is mainly due to geometric characteristics of the hull (large flared forms at fore and aft part of the hull with small values of volume below waterline at lower draughts), which increase vulnerability to parametric rolling and pure loss of stability.

Another difference between the two groups of ships is of that the first group includes slow speed ships (tankers, bulk carriers, etc) whilst the second group of ships contain relatively high speed ships (container ships, Ro-Ro ships, etc). Based on this observation we can affirm that the waves that are long enough to be capable to induce parametric rolling or pure loss of stability phenomenon are too fast for the slow speed ships (because the time spend on the wave crest is considerable limited than in the case of high speed ships). In this sense, the criteria show no vulnerability to such phenomena for these types of ships that generally is consistent with operational experience.

On the other hand, it may be noted that, the second group of ships are vulnerable to stability failures in waves only in extreme weather conditions with high sea state, where wave height is large. This fact can be a picture that provides a clear separation of ships that are vulnerable only in high seas states from the ships that are vulnerable in almost all sea states.

CHAPTER 4

THE IMPLEMENTATION ON BOARD SHIPS OF THE PROPOSED STABILITY CRITERIA

Proposed onboard procedure for calculation and assessment of ship's dynamic stability in waves

The proposed methodology for calculation and assessment the ship's dynamic stability in waves for phenomena like parametric rolling and pure loss of stability is based on the idea to be a very easy and useful onboard computational tool for ship's officers.

The main aspects taken into consideration when the methodology was developed were:

- All the necessary data for calculation to be available on board vessel and easy accessible to ship's officers.
- To be a not time-consuming methodology.
- To use simple and accurate procedures for calculation.
- The calculation to present relevant parameters based on actual loading condition in order to assist the Master in his judgment on whether the ship is vulnerable or not to dangerous phenomena in severe sea conditions.
- A quick assessment between obtained values and limit values.
- Not involving extra costs from owner's side.

In order to be a not very sophisticated and time-consuming operation, the procedure for onboard calculation and assessment of the dynamic stability in waves can be based on the same principles as the actual existing procedure for the transverse stability calculations. In this way, the procedure of calculation can be performed on a series of calculation sheet forms for each criterion as well as for each level of vulnerability. The proposed procedure for calculation the dynamic stability in waves for assessment ship's vulnerability to parametric rolling and pure loss of stability is presented in the tables 4.2 to 4.4.

Table 4.2 Proposed Calculation Sheet Form for assessment of parametric rolling criteria – Level 1

Calculation Sheet for Parametric Rolling Criteria					
Level 1 – Minimum GM variation for onset of parametric rolling					
			Criteria	***Actual***	***Comply***
1.	Hw	Table 2.3			
2.	dm	from transverse stability calculation			
3.	GMo	from transverse stability calculation			
4.	KGo	from transverse stability calculation			
5.	dU	Eq.(2.21)			
6.	dL	Eq.(2.21)			
7.	BMU	from hydrostatic tables equivalent to dU			
8.	VCBU	from hydrostatic tables equivalent to dU			
9.	BML	from hydrostatic tables equivalent to dL			
10.	VCBL	from hydrostatic tables equivalent to dL			
11.	GMU	Eq.(2.22)			
12.	GML	Eq.(2.22)			
13.	δGM	Eq.(2.23)			
14.	η	Eq.(2.30)			
15.	ω_{φ}	Eq.(2.72)			
16.			$\frac{\delta GM}{GM_0} > \frac{4\eta}{\omega_{\varphi}}$		

Table 4.3 Proposed Calculation Sheet Form for assessment of parametric rolling criteria – Level 2

Level 2 – Areas under GZ curves for parametric rolling response										
Calculation Sheet for righting levers GZU and GZL										
GMo	from transverse stability calculation									
GMU	from Level 1 line (11)									
GML	from Level 1 line (12)									
Angle of	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°

	heel										
1.	sinφ										
2.	GZo										
3.	GZU										
4.	GZL										

Calculation of Areas under GZL & GZU curves (Acrest & Atrough)							
6.	S1	1	4	2	4	1	Simpson coefficients
7.	S1 x GZL						Σ (S1 x GZL)
9.	S1 x GZU						Σ (S1 x GZU)
10.	Acrest	Ac = 1/3 x 10 x Σ (S1 x GZL) x π/180					
11.	Atrough	At = 1/3 x 10 x Σ (S1 x GZU) x π/180					

Ship's position on the parametric rolling risk map					
			Criteria	***Actual***	***Comply***
12.	$\frac{A_{crest}}{A_{trough}}$				
13.	η	from Level 1 line (15)			
14.			Eq.2.60 Eq.2.61 Eq.2.62		

The results of calculations are then plotted into risk map illustrated by figure 4.2 indicating the ship's vulnerability to parametric rolling.

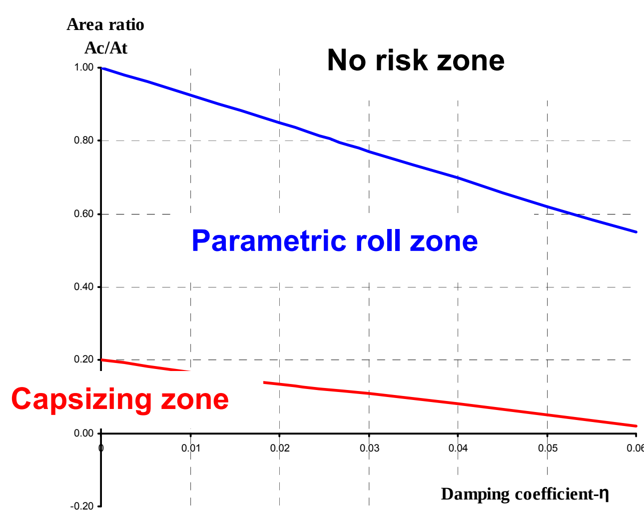

Figure 4.2 Risk map for assessment ship's vulnerability to parametric rolling

Table 4.4 Proposed Calculation Sheet Form for assessment of pure loss of stability criteria – Levels 1 & 2

Calculation Sheet for Pure Loss of Stability Criteria					
Level 1 – Minimum GM on wave crest					
			Criteria	***Actual***	***Comply***
12.	GML	From Level 1 parametric rolling	GML > 0		
Level 2 – Maximum GZ on wave crest					
			Criteria	***Actual***	***Comply***
13.	GZL	Eq.(2.79)	GZmax > 0		

Table 4.5 Proposed Calculation Sheet Form for assessment of pure loss of stability criteria Level 3

Level 3 – Critical time on wave crest					
			Criteria	***Actual***	***Comply***
13.	P2 – P1	As fraction of ship's length			
14.	T_φ	Eq.(2.72)			
15.	V_s	Ship's speed			
16.	$t(x_c)$	Eq.(2.93)			
17.			$\frac{t(x_c)}{T_\varphi} < 1$		

As can be seen from the above tables, the proposed procedure for onboard calculation is simple and accessible.

The results will reveal the fact that the ship indicators of stability safety are the elements of the righting arm curves for crest and trough conditions (comparing with actual procedures that analyze only the righting arm curve in calm sea). Moreover, the results can be considered as enough accurate to judge the condition of the vessel and the vulnerability to dynamic phenomena in waves if the vessel will encounter severe sea conditions during the intended voyage.

CONCLUSIONS

This thesis is a contribution to the effort to introduce advanced methods for assessment of ships intact stability as well as dynamic behaviour of ships in longitudinal waves encountered during severe sea conditions. The highlights of the efforts to approach the proposed topic are given by the theoretical consistency as well as the extensive material developed by numerical research.

The stability criteria proposed in this thesis, provide a framework to assess the ship safety with special emphasis on dynamic instabilities in waves and focused specifically on stability loss scenarios, like parametric rolling and pure loss of stability, which are clearly related to insufficient stability. The models of dynamic stability criteria proposed in this thesis can be considered suitable to be incorporated in the new generation of criteria under development at International Maritime Organization, because they allow the assessment of the dynamic behaviour of ship under a certain type of stability failure mode in waves.

In the present thesis, the author developed a series of original methods, which constitutes the personal scientific and practical contributions.

Practical scientific contributions can be recorded as follows:

1. Development of dynamic stability criteria for the assessment of parametric rolling and pure loss of stability of ships in waves

One of the main contributions of this thesis was the assessment of the two of stability failure modes in waves (parametric rolling and pure loss of stability) made by development of a new stability criteria. The criteria were developed based on extensive analysis of field data and taking into consideration the main factors that affects the dynamic stability, i.e. the waves and the characteristics of the ships (loading conditions as well as hydrostatic particulars).

The characteristic of the main influencing environmental factor (height of waves) was designed, based on an original method, starting from a model that correlates the height of the wave with the speed of the wind. The approach started from the idea that these two factors are accessible on board vessels, to ship's officers, by measuring the wind speed and convert into wave height from the Beaufort scale.

For the assessment of dynamic stability in waves, it was chosen the situation of ship on the wave crest and wave trough in a "frozen" condition. For these situations, started from mathematical models of roll motions, a methodology for assessment the stability variation (metacentric height and righting lever) was developed. Thus, threshold values for assessment parameters that is characterizing the stability in waves such us, variation of metacentric height, righting lever, area under righting lever curve and time spend on the wave crest, were established and were used as a criterion.

A threshold value for a certain parameter, the area ratio under righting lever curves as a function of roll damping coefficient, was developed in form of a risk map, where zones of danger for occurrence of parametric rolling were established.

2. The validation of the dynamic stability criteria for ships vulnerability to parametric rolling and pure loss of stability in waves

Based on the proposed criteria of assessment the dynamic stability of ships in waves it was studied the vulnerability to such situations. From the sample calculations carried out, it was determined the category of ships vulnerable to dynamic instabilities. It was demonstrated that ship's intact stability is in strong connection with the design of the hull, in the sense that a ship with flared forms fore and aft will have less stability on the wave crest due to decreasing of waterplane area. In this respect, through the developed criteria, were identified such type of ships which are possible vulnerable to dynamic instabilities studied.

Practical contribution can be considered as follows:

1. An ample study and analysis regarding the stability failure modes in severe sea conditions

The study was realized on a number of ships, of different type and sizes, that encountered extreme sea conditions, involved in loss of stability casualties. Correlations has been made between casualties and the type and dimensions of ships, type of cargoes carried, geographical area, period of the year as well as characteristics of environmental conditions (wind and waves). Based on this study it was pointed out the possible modes of stability failure in severe seas as well as the causes and factors involved.

It was revealed that most of the stability failure modes presented can not be prevented, by officers on board vessel, as the current stability regulations in force has not providing any guidance in this respect. Based on this study, a criteria of assessment dynamic instabilities of ships in extreme sea conditions has been proposed.

4**. Development of a practical procedure for calculation dynamic stability on board ships**

Based on the idea to be a very accessible and useful onboard computational tool for ship's officers, a practical procedure for calculation of ship dynamic stability was developed. In order to be a not very sophisticated and time-consuming operation, the procedure for onboard calculation and assessment of the dynamic stability in waves is based on a series of calculation sheet forms for each criterion as well as for each level of vulnerability provided by the proposed dynamic stability criteria developed in this thesis.

Having in view the personal contributions (practical and scientific), it can be said that the goal of the thesis has been achieved.

The work studied in this thesis has its own limitations. For the studying in the future, this work may open up a wealth of opportunities. Part of these features already started while some of them need further attention. During the work, there were two main problems addressed: the cohesion between assessment of stability of ships and the effect it has on the safety of navigation.

The interesting and important topics brought into attention, in this work, need further research. The stability failure modes due to phenomena like parametric rolling and pure loss of stability has been assessed in this study only in longitudinal seas (i.e. head or following waves). In this respect, an interesting topic for future research is the effect of quartering waves on such phenomena, having in view that roll motion and damping can be much more complicated in these situations.

The calculation of roll damping by Miller's method is by no means an absolute reference and a further calculation of roll damping can take into consideration the applicability of a different method, like for example Ikeda's method.

The stability failure modes in waves are rather unpredictable in real seas when waves are irregular and coming from different directions. Since parametric rolling or pure loss of stability are not ergodic, the methodology for assessment has to establish the risk of encountering critical conditions for the development of these phenomena. This fact can be achieved with large sample of simulations based on scenario that take into consideration the mainly navigation routes used during operation process of certain types of ships (like for example container ships of certain deadweight capacity on the North Atlantic routes). The results, achieved with accuracy, can be a good instrument for further development of stability criteria.

A further study concerns the waves and more precisely the assessment of parametric rolling based on a critical wave group encountered in real seas scenario. The analysis has to be concentrated on different scenarios of wave parameters or models (like Gaussian wave model or second order non-linear wave model) and to check the method's sensitivity to these variations.

The present work can be a useful tool for maritime organizations to be used for future development of preventing measures, used as guidance (if not as regulations) for officers on board vessels, for avoiding ship's dynamic instabilities in waves. The study conducted in this thesis aimed to bring contribution on optimizing the safety of navigation through a new methodology for assessment of ships stability.

Publications related to the thesis

Lamba M. D., **Andrei C**., Hanzu P.R., *The analysis of intact ship stability regulations*, Constanta Maritime University Annals, Year XIII Vol. 18, ISSN 1582-3601, p. 45-48, 2012.

Andrei C., Lamba M. D., Hanzu P. R., *Behind the theory of safety against capsizing and assessing ship stability***,** Constanta Maritime University Annals, Year XIII Vol. 18, ISSN 1582-3601, p. 25-30, 2012.

Andrei C., Hanzu P. R., *Correlation between safety of navigation and parametric roll of ships in waves***,** Constanta Maritime University Annals, Year XIII Vol. 17, ISSN 1582-3601, p. 27-31, 2012.

Andrei C., Hanzu P. R., Lamba M. D., *The influence of liquid free surface on ship stability*, Constanta Maritime University Annals, Year XIV, Vol.19, ISSN 1582-3601, p. 21-26, 2013.

Andrei C., Blagovest B., *A proposed criterion for the assessment of the parametric rolling of ships in longitudinal waves*, Journal of Maritime Transport and Engineering, Latvian Maritime Academy, Vol.2, No.2, ISSN 2255-758X, p.4-13, December 2013.

Andrei C., Blagovest B., Lamba M. D., *Considerations on broaching phenomenon and its influence on loss of ship stability in following seas*, Constanta Maritime University Annals, Year XIV, Vol.20, ISSN 1582-3601, p. 13-16, 2014.

Andrei C., Lamba M. D., *Surf-riding of a ship in following and quartering waves and vulnerability to loss of intact stability*, Constanta Maritime University Annals, Year XV, Vol.21, ISSN 1582-3601, p. 11-14, 2014.

Andrei C., Lamba M. D., *Shifting of cargo on board ships, a serious threat to loss of intact stability*, Constanta Maritime University Annals, Year XV, Vol.21, ISSN 1582-3601, p. 15-18, 2014.

ANNEX III – CALCULATIONS RESULTS FOR PARAMETRIC ROLLING CRITERIA WITH SHIPS IN LOADED CONDITION

Table 3.28 Results of calculations for parametric rolling criteria Level 1 & Level 2

Failure mode	Parametric rolling						
	Level 1				Level 2		
Ship Type	$\frac{\delta GM}{GM_0}$	$\frac{4\eta}{\omega_\varphi}$	$\frac{\delta GM}{GM_0} > \frac{4\eta}{\omega_\varphi}$	Comply	$\frac{A_{crest}}{A_{trough}}$	η	Risk zone
C1	1.83	1.45	Yes	Failed	0.392	0.016	Yes
C2	2.01	1.51	Yes	Failed	0.369	0.017	Yes
C3	2.28	1.37	Yes	Failed	0.399	0.018	Yes
C4	2.43	1.73	Yes	Failed	0.393	0.019	Yes
C5	2.67	1.79	Yes	Failed	0.193	0.019	Yes
C6	2.85	1.69	Yes	Failed	0.201	0.021	Yes
C7	2.92	2.17	Yes	Failed	0.238	0.024	Yes
C8	3.12	2.26	Yes	Failed	0.241	0.026	Yes
C9	3.38	2.41	Yes	Failed	0.262	0.026	Yes
C10	3.51	3.76	No	Yes	0.438	0.035	Yes
R1	1.84	1.30	Yes	Failed	0.381	0.021	Yes
R2	1.71	1.36	Yes	Failed	0.385	0.022	Yes
R3	1.98	1.81	Yes	Failed	0.413	0.026	Yes
R4	2.14	1.92	Yes	Failed	0.421	0.027	Yes
R5	2.38	2.04	Yes	Failed	0.418	0.031	Yes
R6	2.24	2.17	Yes	Failed	0.347	0.031	Yes
PCC1	0.58	2.95	No	Yes	0.215	0.031	Yes
PCC2	0.67	3.03	No	Yes	0.256	0.035	Yes
PCC3	0.78	3.21	No	Yes	0.274	0.037	Yes
OT1	0.24	2.54	No	Yes	0.798	0.041	No
OT2	0.27	2.84	No	Yes	0.801	0.043	No
OT3	0.21	3.27	No	Yes	0.823	0.046	No
OT4	0.23	3.98	No	Yes	0.846	0.051	No
OT5	0.16	4.28	No	Yes	0.875	0.052	No

OT6	0.16	4.31	No	Yes	0.881	0.057	No
LG1	0.43	2.61	No	Yes	0.698	0.046	No
LG2	0.58	3.47	No	Yes	0.711	0.044	No
MP1	0.95	1.25	No	Yes	0.756	0.038	No
MP2	1.11	1.90	No	Yes	0.813	0.039	No
B1	0.27	2.72	No	Yes	0.788	0.038	No
B2	0.26	2.83	No	Yes	0.791	0.041	No
B3	0.28	2.92	No	Yes	0.791	0.046	No
B4	0.31	3.01	No	Yes	0.800	0.051	No
B5	0.29	3.56	No	Yes	0.800	0.056	No

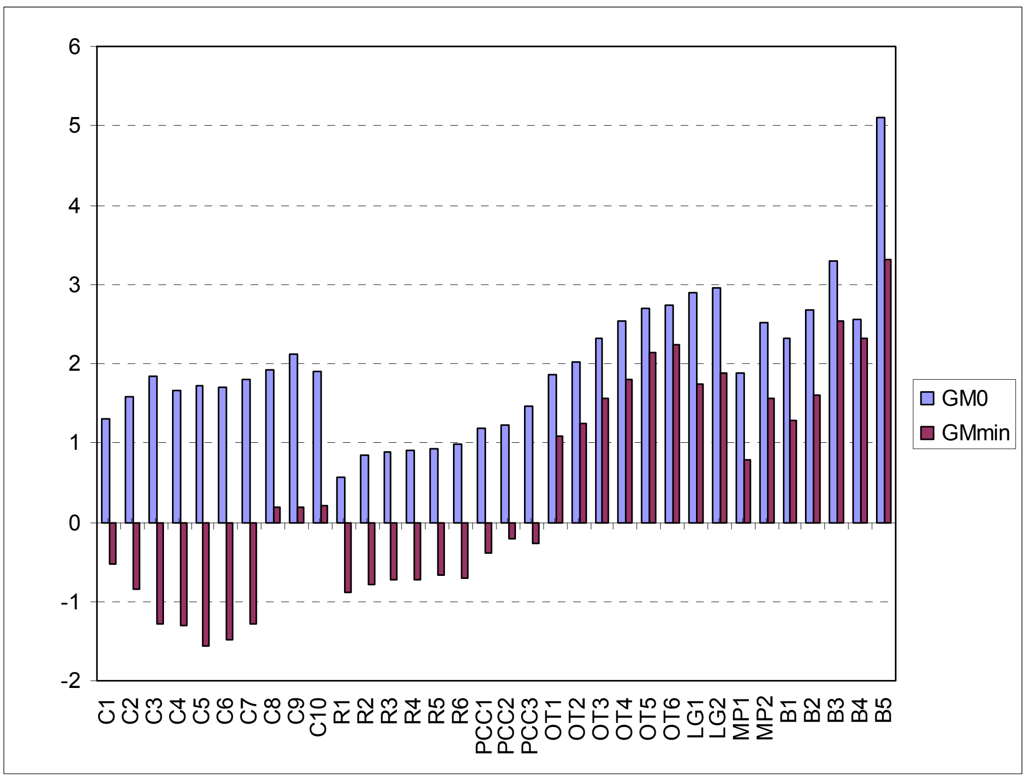

Fig. 3.24 Variation of GM on wave crest

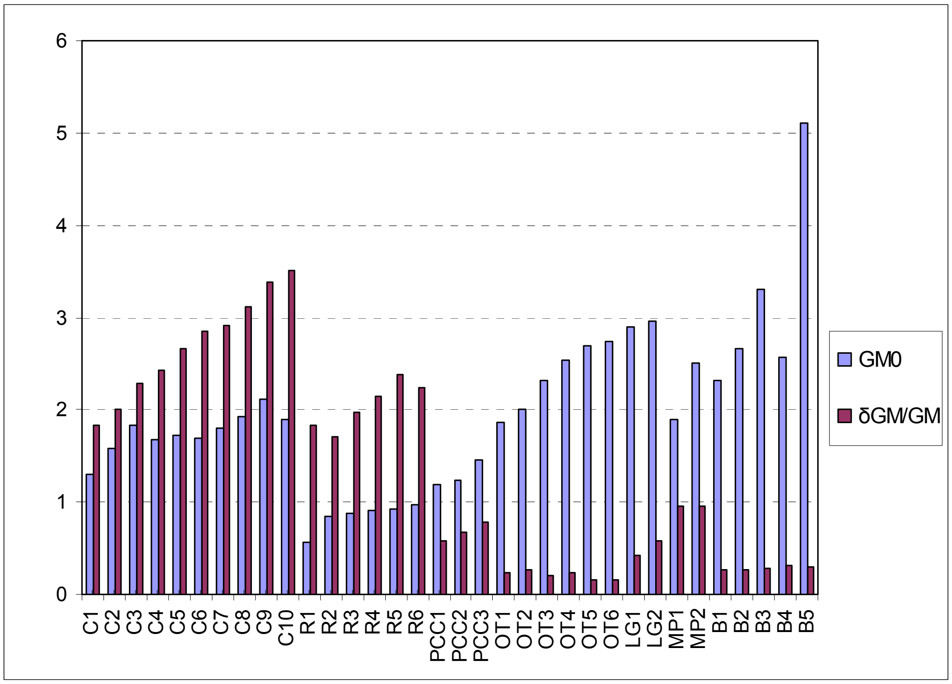

Fig. 3.25 Difference between initial GM and ratio of GM variation in waves

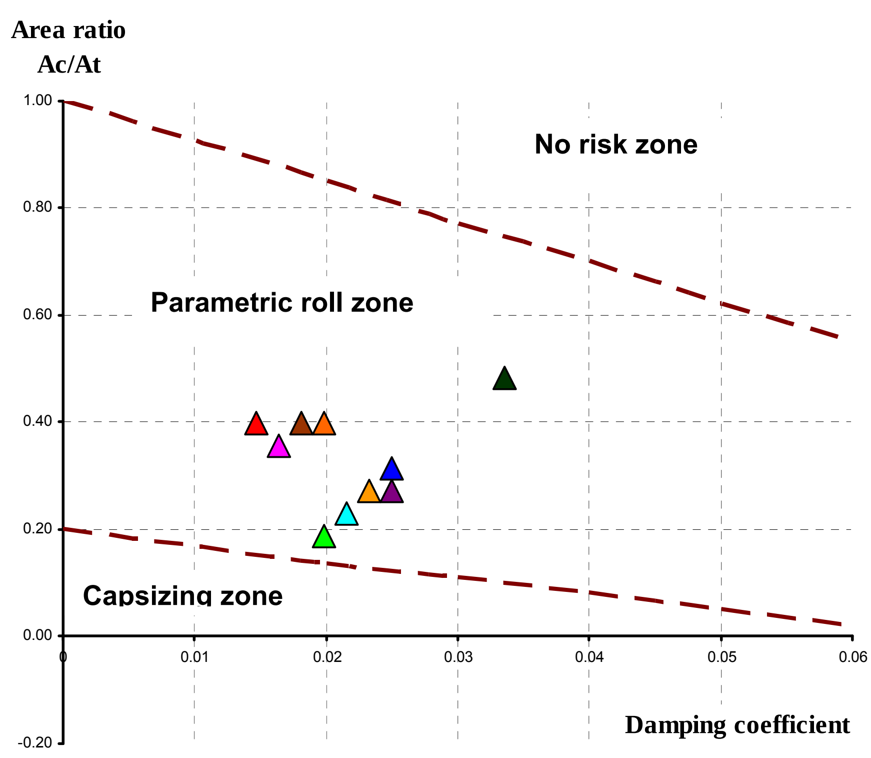

Fig. 3.26 Position of container ships on the parametric roll risk map

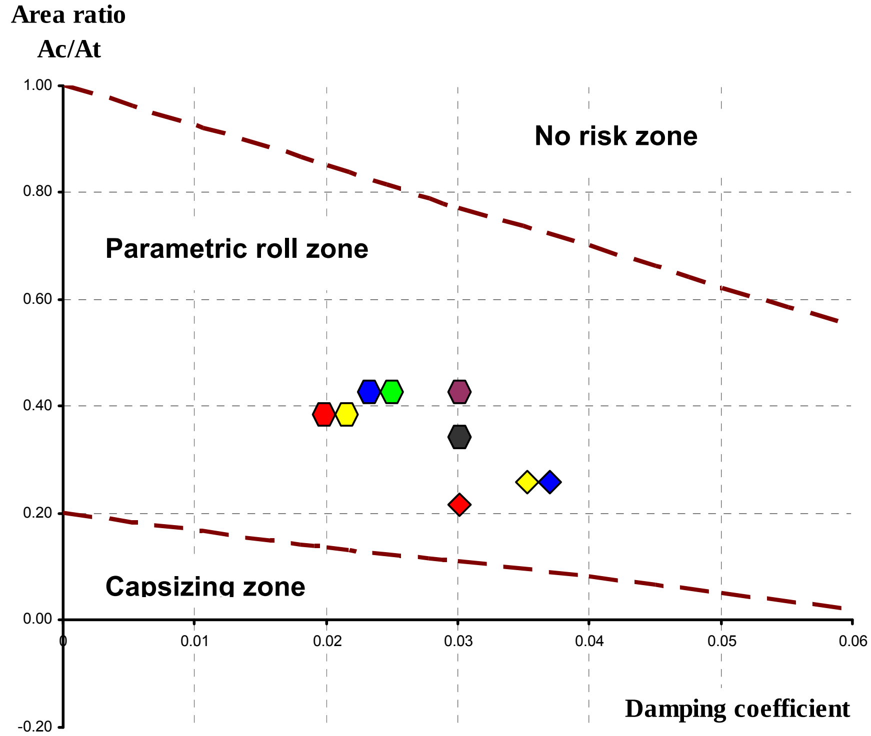

Fig. 3.27 Position of Ro-Ro ships and PCC ships on the parametric roll risk map

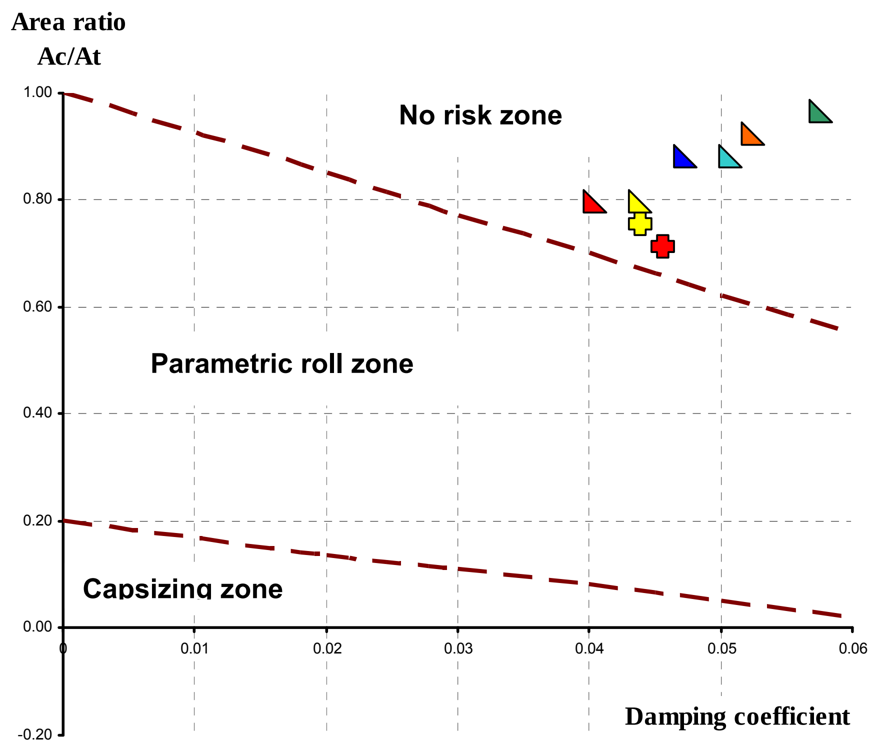

Fig. 3.28 Position of oil tanker ships and gas carrier ships on parametric roll risk map

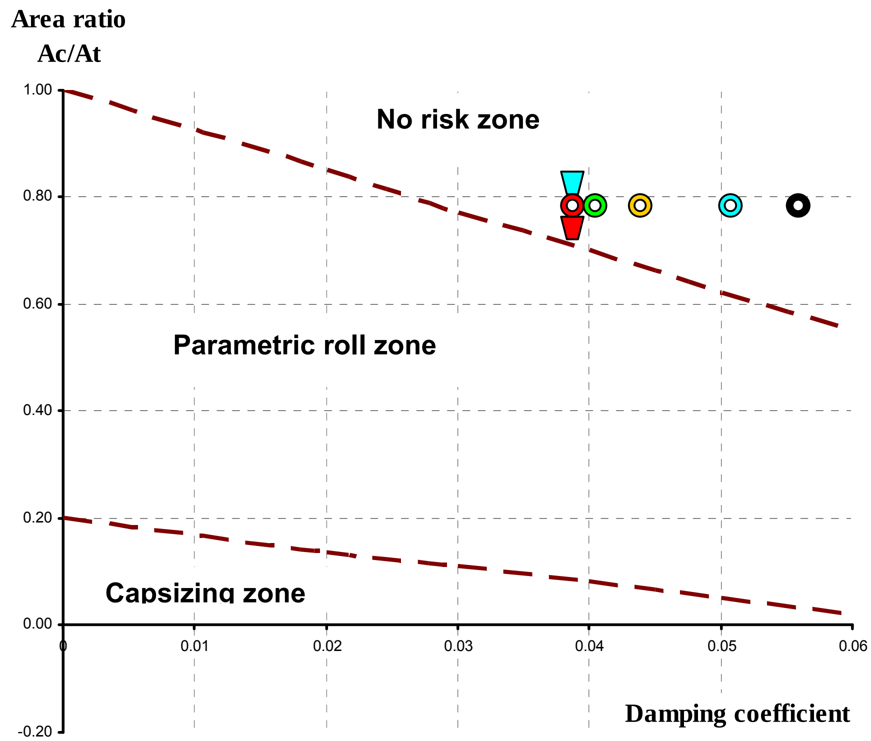

Fig. 3.29 Position of bulk carrier ships and multipurpose ships on parametric roll risk map

ANNEX IV – CATEGORIES OF SHIPS THAT FAILED TO COMPLY WITH PARAMETRIC ROLLING CRITERIA LEVEL 1 & LEVEL 2 (SHIPS IN LOADED CONDITION)

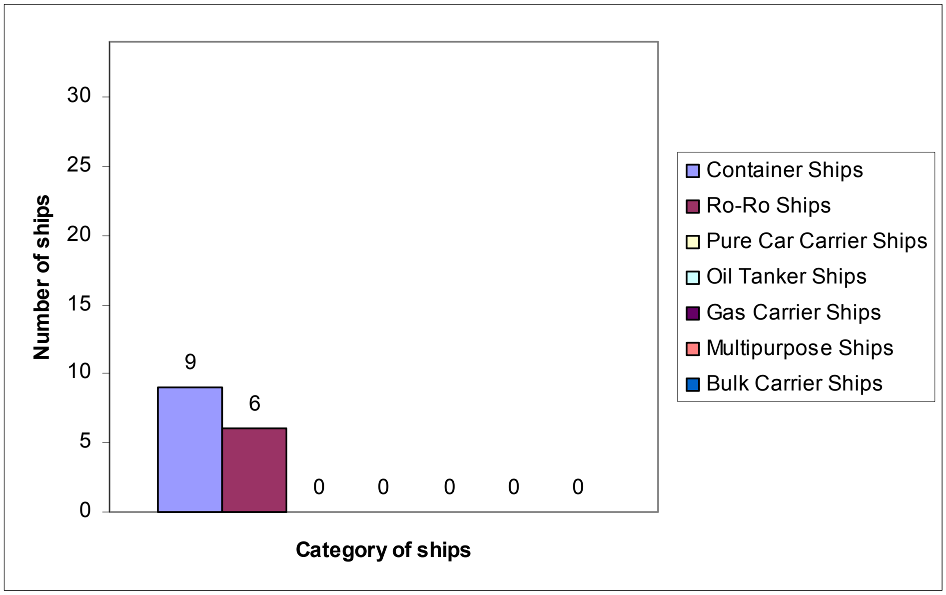

Fig. 3.32 Categories of ships that failed to comply with Level 1 criterion for parametric rolling

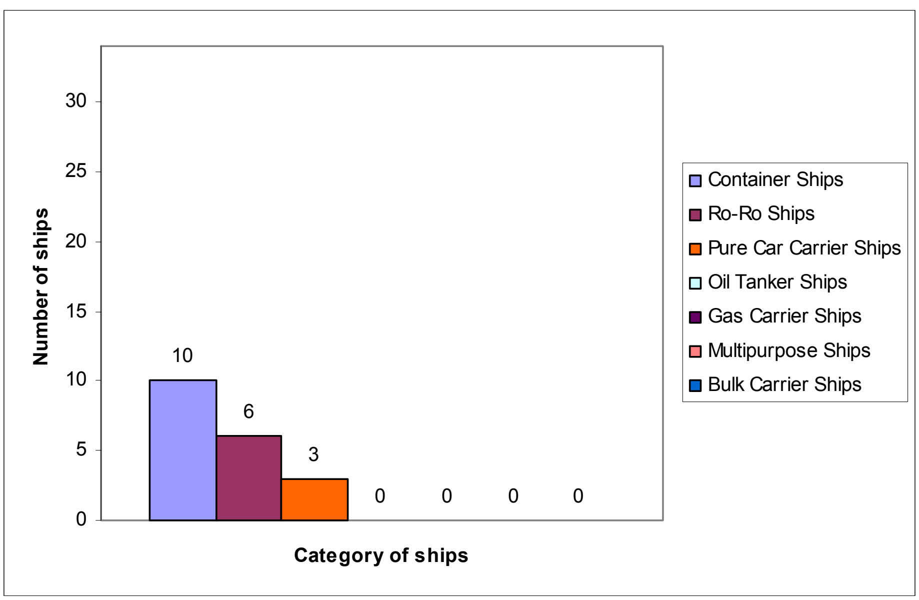

Fig. 3.33 Categories of ships that failed to comply with Level 2 criterion for parametric rolling

ANNEX V – CALCULATIONS RESULTS FOR PURE LOSS OF STABILITY CRITERIA WITH SHIPS IN LOADED CONDITION

Table 3.30 Results of calculations for assessment of pure loss of stability criteria Level 1 & Level 2

Failure mode	Pure loss of stability			
	Level 1		Level 2	
Ship Type	$GM(x_c) > 0$	Comply	$GZ_{max} > 0$	Comply
C1	-0.53	Failed	0.738	Yes
C2	-0.85	Failed	1.025	Yes
C3	-1.29	Failed	1.121	Yes
C4	-1.31	Failed	1.136	Yes
C5	-1.56	Failed	1.143	Yes
C6	-1.48	Failed	1.136	Yes
C7	-1.28	Failed	1.238	Yes
C8	0.18	Yes	1.563	Yes
C9	0.18	Yes	1.571	Yes
C10	0.21	Yes	1.858	Yes
R1	-0.88	Failed	0.251	Yes
R2	-0.79	Failed	0.232	Yes
R3	-0.73	Failed	0.243	Yes
R4	-0.72	Failed	0.264	Yes
R5	-0.67	Failed	0.387	Yes
R6	-0.71	Failed	0.331	Yes
PCC1	-0.38	Failed	0.523	Yes
PCC2	-0.21	Failed	0.711	Yes
PCC3	-0.27	Failed	0.697	Yes
OT1	1.08	Yes	2.916	Yes
OT2	1.24	Yes	3.654	Yes
OT3	1.57	Yes	3.898	Yes
OT4	1.81	Yes	4.418	Yes
OT5	2.13	Yes	4.537	Yes
OT6	2.24	Yes	4.588	Yes

LG1	1.74	Yes	3.561	Yes
LG2	1.88	Yes	3.835	Yes
MP1	0.78	Yes	1.186	Yes
MP2	1.57	Yes	2.231	Yes
B1	1.28	Yes	3.436	Yes
B2	1.61	Yes	3.561	Yes
B3	2.54	Yes	3.875	Yes
B4	2.32	Yes	3.936	Yes
B5	3.32	Yes	4.301	Yes

Table 3.31 Calculation of critical period spent on the wave crest, containerships

	C1			C2			C3			C4		
$P_2 - P_1$	83.5	83.5	83.5	105	105	105	128	128	128	128	128	128
T_φ	19.43	19.4	19.4	20.5	20.5	20.5	19.0	19.0	19.0	24.7	24.7	24.7
V_s	5	10	15	5	10	15	5	10	15	5	10	15
$t(x_c)$	6.1	7.5	9.6	6.7	8.0	9.9	7.2	8.3	9.9	7.3	8.5	10.2
$\frac{t(x_c)}{T_\varphi}$	0.31	0.38	0.49	0.33	0.39	0.48	0.38	0.40	0.48	0.26	0.34	0.41

Table 3.32 Calculation of critical period spent on the wave crest, containerships

	C7			C8			C9			C10		
$P_2 - P_1$	142	142	142	160	160	160	160	160	160	174	174	174
T_φ	25.5	25.5	25.5	24.6	24.6	24.6	23.6	23.6	23.6	26.5	26.5	26.5
V_s	5	10	15	5	10	15	5	10	15	5	10	15
$t(x_c)$	7.6	8.8	10.5	8.1	9.2	10.8	8.0	9.2	10.7	8.4	9.5	11.0
$\frac{t(x_c)}{T_\varphi}$	0.30	0.35	0.41	0.33	0.38	0.44	0.34	0.39	0.46	0.31	0.36	0.42

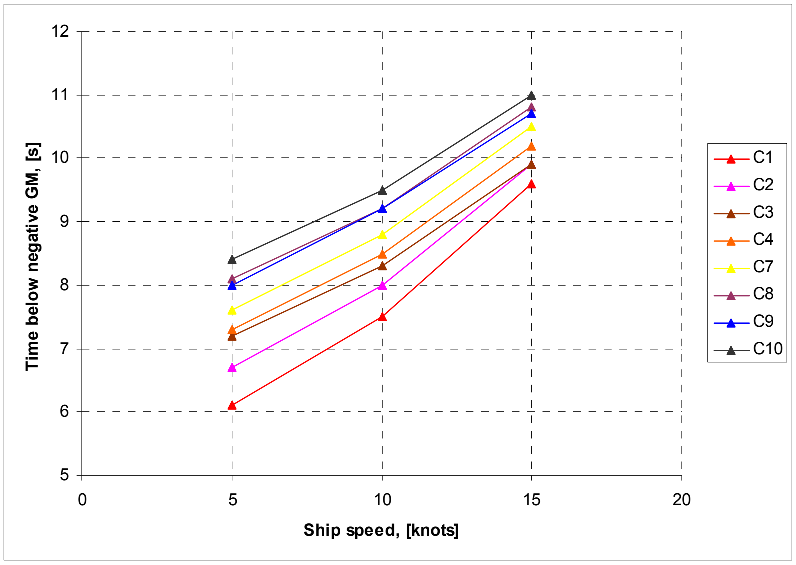

Fig. 3.30 Dependence of time spend on wave crest as a function of ship's speed, containerships

Table 3.33 Calculation of critical period spent on the wave crest, Ro-Ro ships

	R1			R2			R3			R4		
$P_2 - P_1$	46	46	46	50	50	50	53	53	53	61	61	61
T_φ	21.8	21.8	21.8	17.7	17.7	17.7	19.9	19.9	19.9	20.7	20.7	20.7
V_s	5	10	15	5	10	15	5	10	15	5	10	15
$t(x_c)$	4.3	5.6	8.2	4.5	5.7	8.1	4.6	5.8	8.0	4.8	6.0	8.0
$\frac{t(x_c)}{T_\varphi}$	0.20	0.26	0.37	0.25	0.32	0.45	0.23	0.29	0.40	0.23	0.29	0.38

Table 3.34 Calculation of critical period spent on the wave crest, Ro-Ro and PCC ships

	R5			R6			PCC1			PCC2		
$P_2 - P_1$	68.5	68.5	68.5	74	74	74	78	78	78	80	80	80
T_φ	20.6	20.6	20.6	20.1	20.1	20.1	18.0	18.0	18.0	23.3	23.3	23.3
V_s	5	10	15	5	10	15	5	10	15	5	10	15
$t(x_c)$	5.1	6.2	8.0	5.2	6.3	8.1	5.3	6.4	8.1	5.4	6.5	8.2
$\frac{t(x_c)}{T_\varphi}$	0.24	0.30	0.39	0.26	0.31	0.40	0.30	0.35	0.45	0.23	0.28	0.35

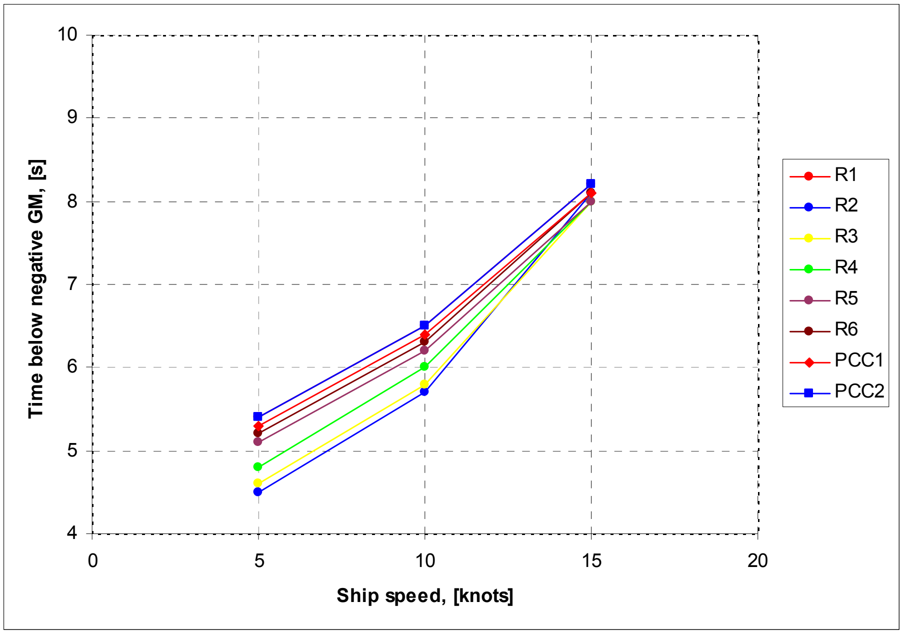

Fig. 3.31 Dependence of time spend on wave crest as a function of ship's speed, Ro-Ro and PCC

ANNEX VI – CATEGORIES OF SHIPS THAT FAILED TO COMPLY WITH LEVEL 1 OF PURE LOSS OF STABILITY CRITERIA (SHIPS IN LOADED CONDITION)

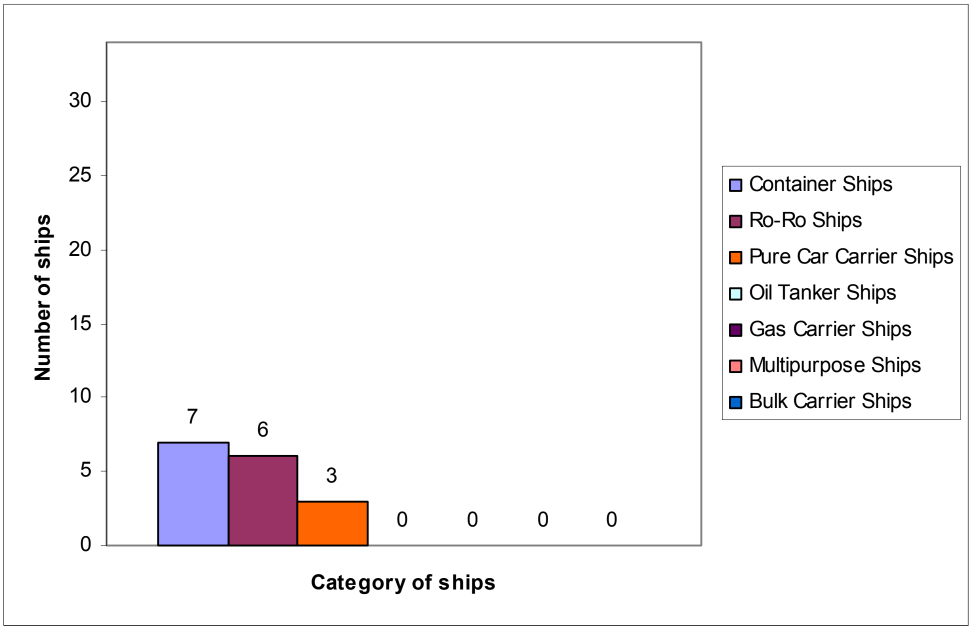

Fig 3.34 Categories of ships that failed to comply with Level 1 criterion for pure loss of stability