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A PROPOSED CRITERION FOR ASSESSMENT THE PURE LOSS OF STABILITY OF SHIPS IN LONGITUDINAL WAVES

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One of the most important nautical qualities of the ship is intact stability. During encountering heavy weather conditions, vessels are exposed to large variations of stability in waves, leading to loss of intact stability or even capsize. One of the phenomena that lead to ship's dynamic instabilities is pure loss of stability in longitudinal waves. The present paper describes a proposed criterion for the assessment of ship's vulnerability to such phenomenon, before starting the voyage, based on the hydrostatic characteristics of the ship and actual loading condition. The proposed method for intact stability loss evaluation in longitudinal waves, when parametric roll might occur, is based on the criterion of the ship's time spent on wave crest condition. This method can be used as a guidance or computational tool for the officers on board vessel.

Keywords: pure loss of stability, waves, criterion.

1. Introduction

The present paper addresses the impact of extreme sea conditions upon intact ship stability. It fits into a complex system of research concerning the intact stability of ships, more exactly to modes of ship stability loss in heavy weather conditions and the possibility of assessment intact ship stability to prevent such losses.

The main objective of the paper is dedicated for the development of a sustainable criterion for assessment ship's intact stability in waves for the phenomena like pure loss of stability. The aim of the proposed criterion is to determine functional and practical relationships between stability principles and applicability on board ships and to be used as guidance, in a form of a computational tool, by ship's officers on board vessel.

The paper presents a new methodology proposed to assessment the pure loss of stability in longitudinal waves in a form of a stability criterion. The difference between the proposed methodology presented in this paper and the

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actual guidelines issued by International Maritime Organization [1] is given by the fact that it offers a possible solution for assessment ship's intact stability from the dynamical point of view as a computational tool with all the data available on board vessel for ship's officers. The guidelines presented in [1] are not providing any ship-dependent information concerning the stability failure mode whilst the information given is in a dimensionless format only by a ratio between ship speed, wave period and the encounter angle.

Moreover, despite the fact that the Classification Society American Bureau of Shipping was the first international authority that issued rules [2], for the assessment of ship stability in extreme seas, the methodology for assessment is based on the calculations that use the data that is not available to ship's officers on board vessel. As a result, the methodology remains for the moment just as guidance for ship's officers but with large applicability in practice, especially in the naval architecture during designing of ships (especially containerships).

Pure loss of stability is a ship stability failure mode by physical phenomena and 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.

In comparison with calm water, naval architects knew differences in the change of stability in waves since late 1800's [3]. However, it was uncommon until the 1960's to try to calculate the change of stability in waves [4] and evaluate it with a series of model tests [5] . Pure loss of stability was identified, as a distinct mode of stability failure, during the model experiments in San Francisco Bay [6], [7].

The change of stability in waves presents certain challenges in the accuracy of calculation [8], especially at high speed, as the waterplane shape and pressure around hull are influenced by the nonlinear interaction between the encountered, reflected, and radiant waves [9], [10].

Pure loss of stability in waves could happen if a vessel encounters a single large wave in following seas and spends a considerable amount of time on the wave crest. During the duration on the wave crest the righting lever of a ship could decrease significantly. In the case of pure following sea, e.g. heading angle of zero degrees, a ship could capsize simply due to loss of static balance by such a reduction of transverse stability.

The alterations of the righting lever, which can be expressed by the differences of the righting levers at the trough and crest condition, are always related to a specific hull form, and resulting in significant changes of hull's wetted surface and waterline area (Figs. 1 and 2).

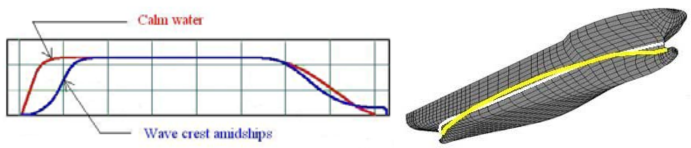

Fig. 1. Change of ship’s waterplane area on wave crest [11]

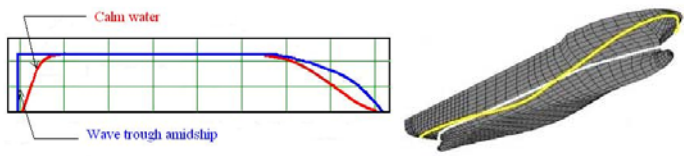

Fig .2. Change of ship’s waterplane area on wave trough [11]

2. Pure loss of stability on board ships

A scenario for the development of ship’s stability failure caused by pure loss of stability is represented below:

First the ship is sailing with relative high speed, (Fig. 3), and a large wave is approaching from the stern. If the speed of the wave is just slightly above the ship speed, the time duration for the wave to pass the ship may be long. There is a typical change of stability caused by large waves, represented by the variation of restoring lever (GZ) and the angle of roll (φ).

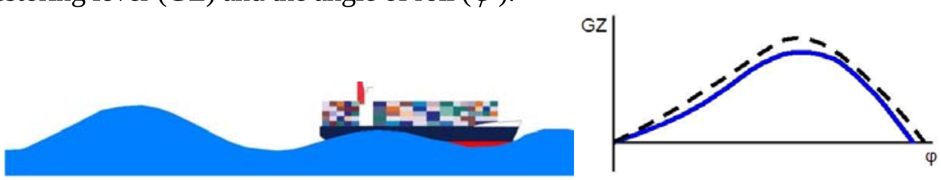

Fig. 3. Vessel sailing in following waves, large wave approaching from stern (left). Changes of stability caused by small relative waves (right) [12]

Then, the large wave is overtaking the ship (Fig. 4). Once the crest of the wave is near the midship and if the ship’s time exposure to the crest is long enough, the restoring moment may decrease significantly and the stability may exceed the minimum limit.

Fig .4. Large wave is overtaking the ship(left). Decrease of stability caused by the wave crest (right) [12]

As the wave crest condition occurs, the intact transversal stability - metacentre height GM_0 and the current restoring lever GZ are significantly decreased [13], [14]. If the intact transversal stability - metacentre height GM_0 becomes negative, the pure stability loss may occur instantaneously. If the wave crest condition period is long enough, there are induced significant roll motions with higher heel angle that might lead to ship capsize.

As the large wave has passed the ship (Fig. 5), the stability is regained and the ship will eventually return to the upright position, if did not already heel too far.

Fig 5. Large wave passed over the ship (left) and the stability is regained (right) [12]

3. The concept of the proposed criteria

The proposed dynamic stability criterion, for the assessment of pure loss of stability in waves, is based on the following levels (Fig. 6):

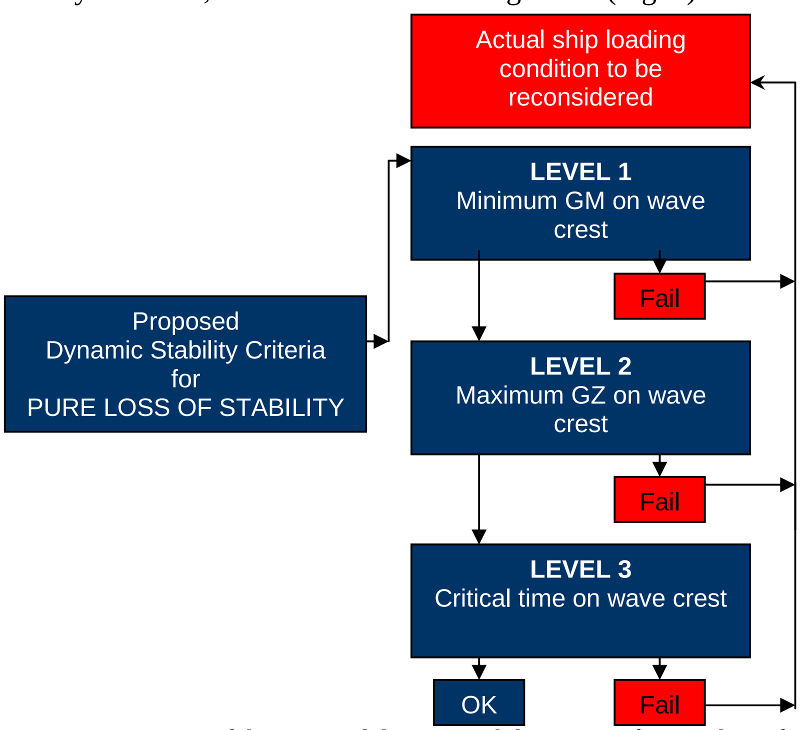

Fig. 6. Structure of the proposed dynamic stability criteria for pure loss of stability

Based on the above aspects, the assessment criteria consider the main following aspects:

- Ship actual loading condition, from where one can deduct the critical KG that leads to critical GM and maximum positive value of GZ on the wave crest. Critical KG is the value above the maximum necessary KG that leads to minimum GM imposed by present IMO stability criteria which is GM to be not less than 0.15m [15].
- The assessment of pure loss of stability is based on correlation between the time of the wave crest passing along the ship's hull and the large heeling angles (indicated by ship's rolling period).

4. Assessment of critical period spend by ship on wave crest

In the present paper is presented only the methodology of calculation of the level 3 from the proposed criterion. This is an extended model of the method presented in [16] 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 this work, the time spent on the wave crest is used as a ratio with the natural roll period of ship for indication of the possibility to develop large angles of heel.

The wave is considered a regular one, with following μ=0 or heading μ=180 condition. In the case of longitudinal waves, the roll motion cannot be directly induced by waves (the roll wave diffraction moment $M_w(t)$ is zero). In this case the parametric roll motion can be induced, due to the variation of the restoring lever GZ(t).

The ship-wave encountering circular frequency, into the mobile ship's coordinates system, is:

$$\omega_e = \omega - \frac{\omega^2}{g} v \cos\mu \,, \tag{1}$$

and for the longitudinal waves $\rightarrow$ $\omega_e = \omega \pm \frac{\omega^2}{g} v \,,$ (2)

where: μ is heading angle, v is the ship speed, ω is wave circular frequency in fix global system and g is gravity acceleration.

The roll motion equation in longitudinal waves case (μ=0 or 180), includes only radiation terms:

$$\left(J_x + A_{44}(\omega_e)\right)\ddot{\varphi} + B_{44}(\omega_e)\dot{\varphi} + g \cdot \Delta \cdot GZ(t) = M_w(t) = 0 \,, \tag{3}$$

where: J_x is the inertial mass moment around Ox axis; A_{44} and B_{44} are the hydrodynamic mass and damping terms function to the ω_e , taking as reference the ship still water position; Δ ship displacement corresponding to the loading case; zero roll wave diffraction moment $M_w(t)$ in longitudinal waves.

Due to the relative position in the vertical plane between ship and wave, considering the wave as regular, the restoring lever has the following time function [17], [18]:

$$GZ(\varphi(t)) = \varphi(t)\cdot GM(t) = \varphi(t)\cdot\left[GM_m - GM_a \cdot \cos\omega_e t\right], \tag{4}$$

where GM_m the average and GM_a the amplitude of the metacentre height in regular wave.

On the crest wave condition the GM(t) decreases and the stability loss occurs when:

$$GM \le 0 \;\rightarrow\; (GM_a / GM_m)\cos\omega_e t \ge 1 \;\rightarrow\; \xi\cos\omega_e t \ge 1 . \tag{5}$$

The parametric roll motion equation becomes:

$$\ddot{\varphi} + 2\rho\dot{\varphi} + \omega_\varphi^2\left[1 - \xi\cos(\omega_e t)\right]\varphi(t) = 0 , \tag{6}$$

where: $2\rho = 0.5\,B_{44}/(J_x + M_{44})$; $\omega_\varphi^2 = g\cdot\Delta\cdot GM_m/(J_x + M_{44})$; $\xi = GM_a/GM_m$

ρ hydrodynamic damping coefficient; ω_φ natural roll circular frequency based on average GM_m metacentre height in regular wave; ξ non-dimensional parametric amplitude of the GM metacentre height in regular wave.

In order to determine the approximate period of time spend by the ship in which the restoring is negative, the following condition can be settled

$$\xi\cos(\omega_e t) > 1 , \tag{7}$$

and thus, the time when the restoring is negative is determined by the relation

$$t_{GZ<0} = \frac{\arccos(\frac{1}{\xi})}{\omega_e} . \tag{8}$$

There is considered a linearised roll equation with equivalent linear restoring coefficient - ε - which takes negative values, $\varepsilon < 0$,

$$\ddot{\varphi} + 2\rho\dot{\varphi} + \varepsilon\varphi = 0. \tag{9}$$

The solution of equation (5) is

$$\varphi(t) = p_1 e^{(-\rho-\sqrt{\rho^2-\varepsilon})t} + p_2 e^{(-\rho+\sqrt{\rho^2-\varepsilon})t} . \tag{10}$$

In order to have non-zero parametric roll oscillations, it is necessary to impose small initial condition (t=0) on roll angle $\varphi(0)$ and angular velocity $\dot{\varphi}(0)$. The p_1 and p_2 coefficients result from the following equations:

$$p_1 = \frac{-\rho+\sqrt{\rho^2-\varepsilon}}{2\sqrt{\rho^2-\varepsilon}}\varphi(0) - \frac{1}{2\sqrt{\rho^2-\varepsilon}}\dot{\varphi}(0) , \tag{11}$$

$$p_2 = \frac{\rho + \sqrt{\rho^2 - \varepsilon}}{2\sqrt{\rho^2 - \varepsilon}} \varphi(0) + \frac{1}{2\sqrt{\rho^2 - \varepsilon}} \dot{\varphi}(0) . \tag{12}$$

For an estimation of the time necessary to reach the critical roll angle, the first term of equation (10) can be neglected (because for negative restoring $\varepsilon < 0$, the first term which is bounded contributed much less than the second term which is unbounded), and in this way, for the condition $\varphi = \varphi_{cr}$, time is obtained from the following solution:

$$t_{cr} \approx \frac{\ln \varphi_{cr} - \ln(\frac{\rho + \sqrt{\rho^2 - \varepsilon}}{2\sqrt{\rho^2 - \varepsilon}} \varphi(0) + \frac{1}{2\sqrt{\rho^2 - \varepsilon}} \dot{\varphi}(0))}{-\rho + \sqrt{\rho^2 - \varepsilon}} . \tag{13}$$

The critical roll angle is the limit value of capsizing and is determined on the same principle used in [15] for weather criterion.

The only unknown term from equation (13) is the linear restoring coefficient - ε - which can be considered from the following principle: the potential energy of the equivalent system with linear stiffness -$\varepsilon \cdot \varphi$- is to be balanced with the potential energy of the exact system with time dependent stiffness.

In this way, if it is considered the phase where the ship goes to the region of negative restoring, the equation (6) of the exact system becomes

$$\ddot{\varphi} + 2\rho\dot{\varphi} + \omega_{\varphi}^2 (1 - \xi \cos(\omega_E t - \arccos \frac{1}{\xi}))\varphi = 0 . \tag{14}$$

Therefore, the equality of potential energies can be expressed as:

$$\int_0^{\varphi_{cr}} \int_0^t \varepsilon \varphi d\varphi dt = \int_0^{\varphi_{cr}} \int_0^t \omega_{\varphi}^2 \left[1 - \xi \cos\left(\omega_E t - \arccos \frac{1}{\xi} \right) \right] \varphi d\varphi dt . \tag{15}$$

The above equation used together with eq.(8) gives the solution of ε, as follows

$$\varepsilon = \omega_{\varphi}^2 \left[1 - \frac{\sqrt{\xi^2 - 1}}{\arccos \frac{1}{\xi}} \right] . \tag{16}$$

In order to meet that the instability condition, and thus to obtain the critical value of parametric amplitude, it is necessary that the time when the restoring is negative is higher than the critical time necessary to reach the roll angle

$$t_{GZ<0} \geq t_{cr} . \quad (17)$$

The positions P_1 and P_2 is indicating the interval when the GM remains negative while the ship is on the wave crest, based on the same consideration used in IS Code 2008.

This interval can be expressed as

$$t(x_c) = \frac{P_2 - P_1}{c_w - V_s} , \quad (18)$$

where, V_s is the ship's speed and c_w is the wave celerity calculated from the relation

$$c_w = \frac{\lambda}{T_w} = \sqrt{\frac{g}{2\pi} \cdot \lambda} = \sqrt{1.56 \cdot \lambda} = 1.25 \cdot \sqrt{\lambda} . \quad (19)$$

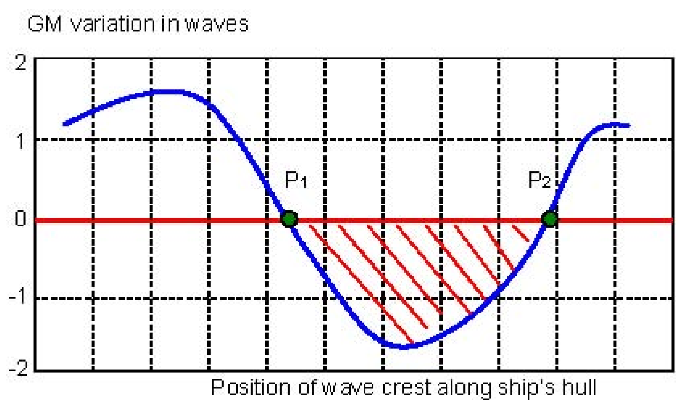

Fig. 7. Position over the ship length [m] of the wave crest with negative GM [15]

The distance $(P_2 - P_1)$ may be 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.

Fig. 8. Fractions of the ship's length, container ship [19]

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 9.

Fig. 9. Fractions of the ship's length, car carrier ship [20]

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

$$\frac{t(x_C)}{T_\varphi} \geq 1, \tag{20}$$

that can be used as a possible criterion for indicating the possibility of the ship to develop large roll angles 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.

5. Validation of the proposed criteria

In order to show the sustainability of the proposed dynamic stability criteria for the assessment of pure loss of stability, the sample calculations were carried out for a number of 16 ships of different types and sizes (marked by C for container ships, R for Ro-Ro ships and PCC for Pure Car Carrier ships) (table 1). All ships used for sample calculations are real and well documented ships, with well defined geometry and load cases. Part of the ships used here, were also used for sample calculations by the Correspondence Group on Intact Stability, established by IMO's SLF Subcommittee, in the reports SLF 53/INF.10 [21] and SLF 54/INF.12 [21] that contains status of developments for new dynamic intact stability criteria.

Table 1

Main characteristics of ships used for sample calculations

Ship Type		LBP (m)	Breadth (m)	Depth (m)	Draught (m)	GM (m)
Containerships	C1	167.00	27.60	15.90	10.70	1.298
	C2	210.00	32.24	18.70	10.50	1.58
	C3	256.50	32.20	19.10	12.50	1.839
	C4	257.40	40.0	21.70	13.50	1.67
	C5	262.00	40.00	24.70	12.43	1.724
	C6	265.80	40.30	24.10	14.00	1.697
	C7	283.80	42.80	24.20	14.00	1.803
	C8	319.00	42.80	24.60	14.50	1.93
	C9	320.00	42.80	24.80	14.65	2.11
	C10	348.00	45.60	29.74	15.53	1.90
Ro – Ro Ships	R1	110.50	20.40	6.80	5.00	0.563
	R2	120.40	20.40	6.80	5.00	0.851
	R3	127.50	23.40	8.60	5.80	0.883
	R4	147.00	24.80	7.90	6.15	0.915
	R5	164.60	24.80	9.00	6.00	0.921
	R6	178.00	24.90	9.26	6.24	0.978
Pure Car Carriers	PCC1	187.70	24.50	21.32	6.90	1.19
	PCC2	192.00	32.26	31.70	8.18	1.23

The numerical calculations were carried out following the methodology described in Chapter 4.The calculations were performed only for the situations of exactly longitudinal waves (head or following waves), and not for the oblique longitudinal waves, and only two wave crest positions were used, wave crest and wave trough amidship. The calculations were based on the consideration that for every ship the wave length is equal with the ship’s length in order to fulfill the main condition for parametric rolling and pure loss of stability phenomena, as the change in stability is most evident for this condition [11].

Sample calculations for assessment of pure loss of stability were performed following the methodology of calculation the critical period spent on the wave crest, described in the proposed stability criteria. The results are illustrated in the tables 2 to table 5 also in the figures 10 and 11.

Table 2

Calculation of critical period spent on the wave crest, container ships in full loaded condition

	C1			C2			C3			C4		
$P_2 - P_1$ [m]	83.5	83.5	83.5	105	105	105	128	128	128	128	128	128
T_φ [s]	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 [m/s]	5	10	15	5	10	15	5	10	15	5	10	15
$t(x_c)$ [s]	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

Calculation of critical period spent on the wave crest, container ships in full loaded condition

	C7			C8			C9			C10		
$P_2 - P_1$ [m]	142	142	142	160	160	160	160	160	160	174	174	174
T_φ [s]	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 [m/s]	5	10	15	5	10	15	5	10	15	5	10	15
$t(x_c)$ [s]	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

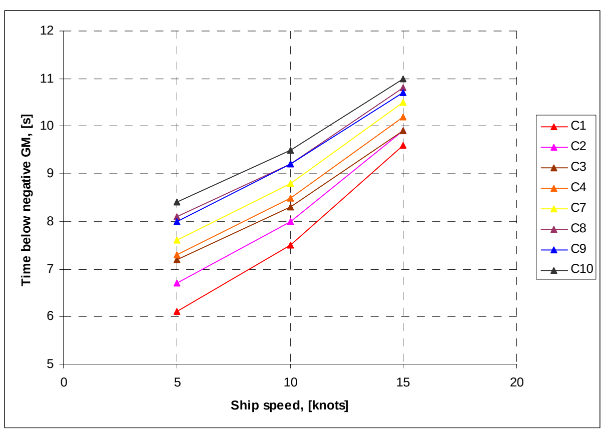

Fig. 10. Dependence of time spend on wave crest as a function of ship's speed, container ships in full loaded condition

Table 4

Calculation of critical period spent on the wave crest, Ro-Ro ships in full loaded condition

	R1			R2			R3			R4		
$P_2 - P_1$ [m]	46	46	46	50	50	50	53	53	53	61	61	61
T_φ [s]	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 [m/s]	5	10	15	5	10	15	5	10	15	5	10	15
$t(x_c)$ [s]	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 5

Calculation of critical period spent on the wave crest, Ro-Ro and PCC ships in full loaded condition

	R5			R6			PCC1			PCC2		
$P_2 - P_1$ [m]	68.5	68.5	68.5	74	74	74	78	78	78	80	80	80
T_φ [s]	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 [m/s]	5	10	15	5	10	15	5	10	15	5	10	15
$t(x_c)$ [s]	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

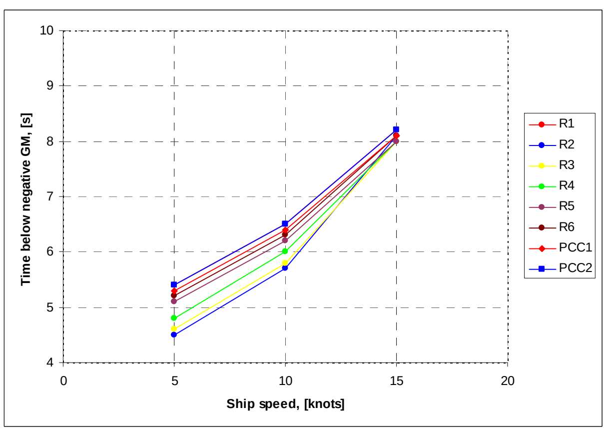

Fig. 11. Dependence of time spend on wave crest as a function of ship's speed, Ro-Ro and PCC ships in full loaded condition

The results revealed the fact that the condition for pure loss of stability, $\frac{t(x_C)}{T_\varphi} \geq 1$, is satisfied for all ships used in sample calculations. It means that all the container ships, Ro-Ro and PCC ships are vulnerable to loss of intact stability due to pure loss of stability phenomenon.

These types of ships are vulnerable to such phenomenon mainly due to large restoring variations which is the result of the geometric characteristics of the hull (large flare forms and fore and aft part of the hull with small values below waterline).

The results consolidate the affirmation that modern designed container ships are known for the vulnerability to stability failures in waves, especially for parametric rolling and pure loss of stability [23].

6. Conclusions

The paper offers a criterion of assessment for the ships dynamic stability in waves, more precisely the possibility of assessment of the ship's vulnerability due to dynamic instability generated by the pure loss of stability phenomenon.

The proposed criterion can be useful for officers on board ships in order to determine the ship's vulnerability to pure loss of stability prior to the start of the intended voyage, considering the actual ship loading condition. Moreover, the method can be integrated as an additional dynamic stability criterion into already existing one for the assessment of intact ship stability in waves.

The subject can be considered as a contribution to the efforts to introduce new and advanced methods of assessment of ship stability in longitudinal waves with a possible practical application in designing of new generation of ships.

Having in view that the method was studied only for longitudinal waves (head and following waves) further studies can be carried out for quartering waves.

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