A stability in waves assessment of self-righting vessels

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Abstract. Self-righting vessels, usually used for Search and Rescue (SAR) missions, are characterized by specific stability performance enabling the vessel to regain the upright condition, after possible capsizing due to heavy sea conditions. This requires a demanding design process aimed to provide the proper combination of centre of gravity position and geometry features; these last in turn are requested also to fulfil the significant high-speed performance, usually characterizing the SAR vessel operational profile. The resulting hull shape may be an interesting investigation case to be analysed in terms of stability in waves performance. The Second Generation Intact Stability criteria, recently finalized at IMO, provide a robust reference to derive physical modelling and criteria to carry out a stability assessment in this perspective. The paper considers two application cases relevant to real cases of self-righting vessels for maritime safety and protection, with dimensions positioning the vessels in the medium-high size range, with reference to the category, together with a speed of more than 18 knots. Stability failures are going to be investigated with a specific focus on Broaching and Loss of stability in waves; some specific parameters will be selected to put in evidence their influence on the vessel stability in wave behaviour.

Keywords. Stability in Waves, Self-Righting Vessels, Second Generation Intact Stability criteria, Surf-Riding.

1. Introduction

Self-righting vessels are specifically designed to re-establish the upright position in case of capsizing. Actually, this capability can be implemented as an inherent property of the vessel or provided by the installation of systems onboard, assisting/enabling the righting performance. In this paper we are dealing with the former case, relying therefore basically on centre of gravity position and vessel geometry, as already intrinsic unit property. The risk of capsizing phenomenon is considered a plausible option since such boats are characterized by a severe operational profile, with extreme dynamical scenario in terms of speed and environmental condition (waves and wind). In fact, this kind of vessel is engaged in services such as Lifeboat services (e.g., RNLI in the UK), Search and Rescue (SAR) operations, military and coast guard units, pilot and offshore support

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vessels. During the design process of a self-righting unit, by means of proper decisions, safety in extreme sea conditions is aimed as a top priority.
As already mentioned, key design features are the position of the centre of gravity and the buoyancy distribution provided by the hull but also by the superstructure geometry: in fact, the latter is characterizing the buoyancy features when the ship is upside down and the relevant influence on restoring capability. Of course, in this perspective, due care is to be paid to the watertightness of the upper part, usually not the focus when designing other vessels, mainly provided only by weathertightness. Moreover, to prevent floodings during the roll over, it is essential to properly design the internal arrangement in order to protect crew and equipment. Self-righting property is the target performance that nevertheless shall not imply damages or injuries during capsize and roll over.
A specific focus of this paper is to analyse the safety of these special units in rough waters. As it will be more detailed in the next section, while delivering the Intact Stability (IS) Code [1], at the International Maritime Organization (IMO) it was recognized that the safety of a ship in a seaway involves complex hydrodynamic phenomena that require further research. In this perspective, the Secon Generation Intact Stability criteria (SGISc) have been developed, enabling the assessment of ships in terms of stability in waves.

In this paper, after a brief description of the SGISc framework, an assessment will be carried out for selected cases of self-righting units. The aim is to investigate whether the stability characteristics necessarily implemented to provide the self-righting behaviour may expose to failures in terms critical dynamic stability phenomena in waves. In particular, specific attention will be given to the righting lever variations due to the wave profile (only environmental waves will be considered, the steady wave profile due to the ship speed will be neglected) and to the manoeuvring related phenomena such as surf riding/broaching (very relevant due to the medium/high speed of such unit in operations).

2. Second Generation Intact Stability criteria

In recent years, the IMO worked on further improvement of the intact stability regulations for merchant ships contained in the IS code [1]. In the preamble of the IS code, three dynamic phenomena have been identified, possibly leading to a set of dangerous stability failures: parametric rolling (PR), pure loss of stability (PL), dead ship condition (DS), excessive acceleration (EA), and surf-riding/broaching-to (SR). The phenomena are quite complex, and many valuable studies describing the physics behind each of them can be found in literature [2, 3]. Finally, in 2020 and 2022, the interim guidelines [4] for the SGISc and its explanatory notes [5].. The SGISc rely on a multilayered approach: three different levels have been defined for each stability failure, with increasing accuracy but also with higher complexity.

The first level (Lv1) and the second level (Lv2) are called vulnerability levels. Several applications and studies on vulnerability levels can be found in literature [6, 7, 8]. The third level is called the direct stability assessment (DSA): it requires an enhanced time-domain non-linear numerical tool or a model tank test. Studies on the DSA have been published by several authors among which [9, 1011, 12]. The latest version of the criteria explicitly notes that there is no hierarchy among levels; therefore, a loading condition is deemed not vulnerable to a stability failure if at least one level is met.

Besides the vulnerability level implications during the design phase, SGISc introduce the operational aspects related to the navigation by operational measures. Operational measures can be divided into operational limitation (OL) and operational guidance (OG). The former sets restrictions on the navigation related to the environmental conditions; the latter provides suggestions to the master on how safely handle the vessel in dangerous sailing conditions (i.e., a combination of sea state, route, and speed). Applications of OL and OG can be found in the literature [13, 14, 15].

2.1. First vulnerability levels

The first vulnerability levels for PR and PLS analyse the hull stability performances addressing the effects of waves on the transverse metacentric height.

- According to the first vulnerability level for PR, a ship is judged not vulnerable if compliant with (1).

$$\frac{\Delta GM_1}{GM_{calm}} \leq R_{PR} \quad (1)$$

  where ΔGM_1 is the amplitude of metacentric height variation in waves (m), GM_{calm} is the transverse metacentric height in calm water (m) and ΔGM_1 is the standard, i.e. the threshold, defined as a function of main ship dimensions, amidships coefficient and bilge keel area (-);
- According to the first vulnerability level of PLS, a ship is judged not vulnerable if compliant with (2). GM_{min} is the minimum metacentric height in wave (m).

$$GM_{min} \geq 0.05\ m \quad (2)$$

The IMO procedures for PR and PLS perform traditional uprights hydrostatic calculation considering only two even keel waterlines respectively located at the crest and at the through level of a sinusoidal wave characterized by a length equal to the ship length and a fixed wave slope value.

In both PR and PLS criteria, tumblehome hulls should be assessed directly by the second vulnerability level. This typology of hulls is identified by (3).

$$\frac{\nabla_D - \nabla}{A_W \cdot (D - d)} \geq 1.0 \quad (3)$$

where ∇_D (m^3) is the hull volume at a waterline equal to D, that is the moulded depth up to weather deck (m), while ∇, A_W and d are respectively the hull volume (m^3), the waterplane area (m^2) and the draught (m) corresponding to the loading condition under consideration.

As concern DS, the first vulnerability level reflects exactly the so-called weather criterion reported in the IS code [1]. A minor change to the table relating ship natural roll period to the wave steepness has been introduced. The assessment on EA considers a loading condition not vulnerable if compliant with (4).

$$C = \varphi \cdot k_L \cdot \left(g + \frac{4\pi^2 \cdot h_r}{T_{nat}^2} \right) \leq 4.64\ m \cdot s^{-1} \quad (4)$$

where φ is the characteristic roll amplitude (-), k_L is a coupling factor taking into account simultaneous roll, pitch, and yaw motions (-), g is the gravity acceleration (m·s^{-1}), h_r is the vertical position above the roll axis where crew and/or passengers may be present (m), and T_{nat} is the natural roll period (s). Finally, first vulnerability level for SR considers a ship not vulnerable if compliant with (5).

$$Fn \leq 0.30 \qquad \text{and} \qquad L > 200\ m \tag{5}$$

where Fn is the Froude number (-), and L is the ship length (m).

2.2. Second vulnerability levels

The second vulnerability criteria share a common methodology for the long-term assessment, though they differ mainly by the short-term evaluations. The short-term probability failure index is calculated for each sea state defined in the selected scatter diagram. Each stability failure mode has a specific procedure to evaluate the short-term index. Subsequently, the long-term failure index is computed as shown in (6).

$$C = \sum_{i=1}^{N} C_{S,i} \cdot W_S \tag{6}$$

where C is the long-term failure index (-), $C_{S,i}$ is the short-term failure index (-) and W_i is the weighting factor (-) representing the sea state occurrence.

For the PL, the short-term criteria rely on geometric analysis, considering the effect of several wave profiles on hull stability, aimed at identifying the vanishing angles and stable heel angle. The short-term criteria for the PR have a different approach: one criterion studies the effect of several wave profiles on the metacentric height variation, while the second short-term criterion assesses the maximum roll angle achieved by a simplified one-degree-of-freedom time-domain simulation. For the SR, the short-term criterion is computed by an iterative procedure involving the hull resistance curve, the propeller characteristics curves, and the wave surging force. The DS short-term criterion is obtained by an analysis of the roll moment response spectrum considering the effects of waves and wind. Finally, for the EA, the short-term criterion is evaluated by the study of the response amplitude operator for lateral accelerations.

3. Application case

The paper aims at analysing two different types of SAR vessels, one realized in 5 units and used by Coast Guard since 1990 and the other developed for an international shipyard in the beginning of 2000. The two units have been selected considering the design philosophy applied to the project: for the self-righting capabilities both of them rely on the design of the superstructure and the weight distribution and are designed to be subjected to a complete roll over and then continue operating. This characteristic is different from smaller units, where the self-righting system can be realized with inflatable system.

The two boats examined have an interesting difference in terms of shape of the hull: the first one, namely unit Alpha, presents a typical NPL hull, designed to operate with a maximum speed of 18-20 knots; while the second one (namely, unit Bravo) has a planning hull capable of a maximum speed of 25 knots. Main characteristics have been

Table 1. Main characteristics of the investigated units

Main Characteristics		
Unit name	*Alpha*	*Bravo*
Length (m)	*18.00*	*13.70*
Amidship Depth (m)	*1.22*	*0.95*
Froude N. (-)	*0.77*	*1.11*
L/B (-)	*3.21*	*3.18*
W_{SS}[1] (m)	*3.90*	*2.30*
W_{SS}/B (-)	*0.696*	*0.535*
Lateral Area (m^2)	*59.6*	*31.3*
[1]: Maximum width of the superstructure		

Table 2. Investigated loading conditions

	Alpha		Bravo	
Loading Condition	*Departure*	*Arrival*	*Departure*	*Arrival*
Displacement (t)	*43.1*	*36.6*	*21.3*	*20.96*
LCG (m)	*6.81*	*7.16*	*5.15*	*5.20*
GMt (m)	*1.523*	*1.422*	*0.991*	*1.021*

reported in Table 1. The W_{SS}/B (where W_{SS} is the maximum width of the superstructure) is noticeable because of its impact on the capability of self-righting. In order to enhance the investigation, two different loading conditions have been evaluated for each vessel, i.e., departure and arrival loading conditions. Their characteristics have been reported in Table 2.

The two units, even though both representative of the self-righting vessels category, have some significant differences that have been considered of interest for the research, representing the starting point to apply the SGISc. It should be noted that SGISc are applicable to vessel over 24 m in length, however, due to their physical approach they can be deemed suitable to all kind of vessels.

4. Results

In this section the results of the SGISc assessment are presented. The GZ curves for the Alpha unit with and without the superstructure have been shown in order to appreciate the improved stability characteristics (Figure 1). It can be seen that after 60° of heel the superstructure contributes to notably improve the righting arm value.

From Table 3 and Table 4, the outcomes of the direct application of all stability failures and vulnerability levels (i.e., Level 1 and Level 2) to the above-described units are presented. Values of each criterion have been evaluated according to formulas reported in Section 2. Due to the particular shape of the hull side of both the units, the calculation of Level 1 for PR and PL does not consider the check on the hull shape defined in (3). For the Level 1 of SR, the criterion is shown in terms of Froude number and the hull length, respectively. Due to a lack of information about hull resistance at arrival condition, Level 2 for SR for Alpha and Bravo units has been not calculated.

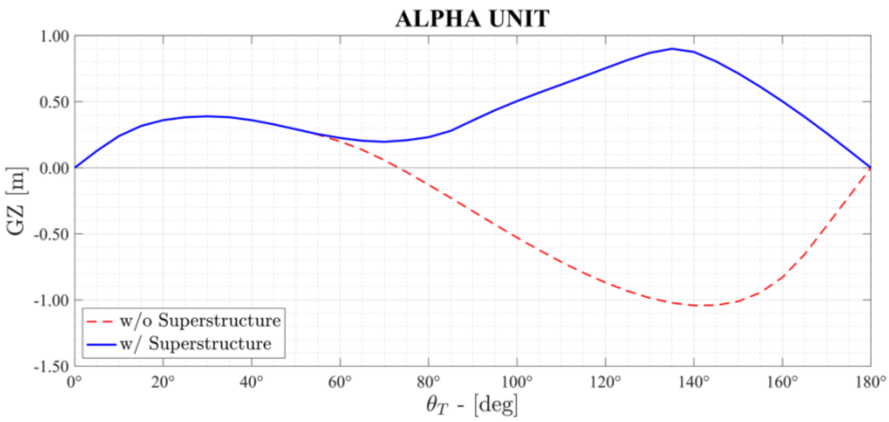

Figure 1. GZ curves of Alpha unit at departure loading condition. Continuous line represents the GZ curve considering the superstructure, the dashed line represents the GZ curve without the superstructure.

Outcomes show that both units are not vulnerable to the PR and PL. As expected, both units are deemed vulnerable to the EA and SR: the former can be ascribed to the enhanced stability performance in the upright condition; the latter can be ascribed to the high design Froude number at service speed and to the relatively small lengths of the hull. Finally, only the Alpha unit is considered vulnerable to the DS, which is consistent with the fact that its exposed lateral area is nearly twice that of the Bravo unit.

Subsequently, the VCG limiting values for each investigated loading conditions are presented for all failure modes. SR failure mode has not been considered since the criteria structure does not consider the VCG parameter. Regarding limiting VCG values, it is worth noting that the EA limiting VCG value represents the minimum threshold to comply with the corresponding criteria. In addition, the final value of each failure mode is obtained by selecting the maximum value between levels (the opposite for the EA failure mode).

Table 3. SGSIc vulnerability assessment for Alpha unit.

Alpha unit - Departure Condition					
Criteria	***PR***	***PL***	***DS***	***EA***	***SR***
Level 1	0.254	0.456	0.0065	16.02	0.73 16.6
Level 2	0.0 0.0	0.0 0.0	0.7666	7.85e-2	0.0344
Final Assessment	MET	MET	NOT MET	NOT MET	NOT MET
Alpha unit - Arrival Condition					
Criteria	***PR***	***PL***	***DS***	***EA***	***SR***
Level 1	0.328	0.384	0.000	16.56	0.73 16.6
Level 2	0.0 0.0	0.0 0.0	0.7777	1.08e-1	n/d
Final Assessment	MET	MET	NOT MET	NOT MET	NOT MET*

*: It does not consider the outcome of Level 2.

Table 4. SGSIc vulnerability assessment for Bravo unit.

Departure Condition					
Criteria	***PR***	***PL***	***DS***	***EA***	***SR***
Level 1	0.076	0.800	2.107	12.60	1.17 12.4
Level 2	0.0 0.0	0.0 0.0	0.743	2.13e-2	0.0210
Final Assessment	MET	MET	MET	NOT MET	NOT MET
Arrival Condition					
Criteria	***PR***	***PL***	***DS***	***EA***	***SR***
Level 1	0.088	0.664	1.240	13.15	1.17 12.4
Level 2	0.0 0.0	0.0 0.0	0.754	1.46e-2	n/d
Final Assessment	MET	MET	MET	NOT MET	NOT MET*

*: It does not consider the outcome of Level 2.

Outcomes have been reported in Table 5 and Table 6. Results point out that limiting VCGs for PR and PL are higher than those provided by the IS code criteria; therefore, the units will never be in that situation. As concern EA, the minimum VCG values are quite higher than the design VCG values. Therefore, it may lead to deem that a compliance with EA criteria is not feasible for the investigated units. Finally, considering the design VCG values, the upper threshold for the DS confirms that there is no design domain for the Alpha unit, while a narrow margin is still available for the Bravo unit.

Table 5. Limiting VCG values for Alpha unit.

Departure Condition					Arrival Condition				
Limiting VCG (m)	***PR***	***PL***	***DS***	***EA****	**Limiting VCG (m)**	***PR***	***PL***	***DS***	***EA****
Lv1	1.42	2.53	1.92	3.40	***Lv1***	0.72	2.46	1.80	3.50
Lv2	3.54	3.54	0.00	3.18	***Lv2***	3.63	3.63	0.00	3.28
Final value	3.54	3.54	1.92	3.18	***Final value***	3.63	3.63	1.80	3.28

*: Limiting VCG values for EA represent the minimum threshold to be compliant with the criteria.

Table 6. Limiting VCG values for Bravo unit.

Departure Condition					Arrival Condition				
Limiting VCG (m)	***PR***	***PL***	***DS***	***EA****	**Limiting VCG (m)**	***PR***	***PL***	***DS***	***EA****
Lv1	2.24	2.07	1.40	2.22	***Lv1***	2.40	2.03	1.32	2.39
Lv2	2.28	2.28	0.84	2.11	***Lv2***	2.45	2.45	0.83	2.29
Final value	2.28	2.28	1.40	2.11	***Final value***	2.45	2.45	1.32	2.29

*: Limiting VCG values for EA represent the minimum threshold to be compliant with the criteria.

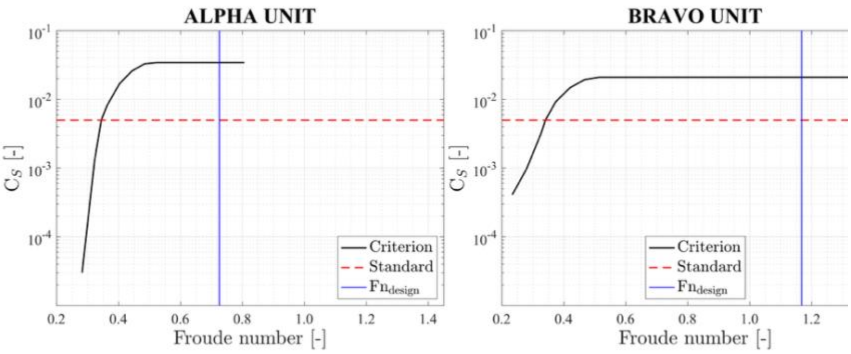

Figure 2. SR criterion for the investigated unit at the departure loading conditions. Results on the left side are referred to the Alpha unit, while right side refers to the Bravo unit.

Moreover, to analyse the vulnerability at the SR of the investigated units, a sensibility analysis on the ship speed has been carried out, as well. Results of this analysis have been reported in Figure 2. On the horizontal axis is reported the Froude number, while on the vertical axis is represented the Level 2 criterion for the SR. The dashed line represents the standard thresholds. Both units should sail at a Froude number lower than 0.34 to be not vulnerable at the SR phenomenon. In addition, both graphs show that when Fn>0.50, the criteria reach a constant trend at the maximum values.

Eventually, to tackle the actual operational profile of the investigated units, the Operational Limitation (OL) related to the geographical area [5] has been applied. Instead of the North Atlantic Ocean, the Central Mediterranean Sea area has been selected in the vulnerability assessment. Outcomes are reported in Table 7 and Table 8. Outcomes confirm the very same results of the plain vulnerability assessment (i.e., considering North Atlantic Ocean area). Regarding the criterion values, the application of OL appears to generally worsen the results.

Table 7. SGSIc vulnerability assessment for Alpha unit.

Alpha unit - Departure Condition					
Criteria	***PR***	***PL***	***DS***	***EA***	***SR***
Level 1	0.394	-0.183	0.0065	16.02	0.73 16.6
Level 2	0.00 0.00	0.00 0.00	0.702	1.02e-01	1.04e-01
Final Assessment	MET	MET	NOT MET	NOT MET	NOT MET
Alpha unit - Arrival Condition					
Criteria	***PR***	***PL***	***DS***	***EA***	***SR***
Level 1	0.502	-0.254	0.000	16.56	0.73 16.6
Level 2	0.00 0.00	0.00 0.00	0.709	1.31e-01	n/d
Final Assessment	MET	MET	NOT MET	NOT MET	NOT MET*

*: It does not consider the outcome of Level 2.

Table 8. SGSIc vulnerability assessment for Bravo unit at departure condition.

Bravo unit - Departure Condition					
Criteria	***PR***	***PL***	***DS***	***EA***	***SR***
Level 1	0.118	0.542	2.107	12.600	1.16 12.4
Level 2	0.000 0.000	0.000 0.000	0.492	4.11e-02	8.00e-02
Final Assessment	MET	MET	MET	NOT MET	NOT MET
Bravo unit - Arrival Condition					
Criteria	***PR***	***PL***	***DS***	***EA***	***SR***
Level 1	0.133	0.357	1.240	13.150	1.16 12.4
Level 2	0.000 0.000	0.000 0.000	0.665	3.26e-02	n/d
Final Assessment	MET	MET	MET	NOT MET	NOT MET*

*: It does not consider the outcome of Level 2.

5. Comments and Conclusions

This work aims to assess the stability performance in waves of self-righting vessels. After a brief overview of this specific vessel typology, the SGISc framework is introduced.

Subsequently, the SGISc are applied to two representative self-righting units, including the limiting VCG curves and OL related to a geographical area.

The outcomes show that neither unit appears vulnerable to the PR and PL failure modes. Regarding the DS failure mode, only the Alpha unit appears vulnerable, which can be attributed to its large lateral exposed area and the relatively high position of the center of that area. The SR and EA failure modes are deemed critical for both units: concerning Alpha unit, this behaviour is aligned with the relatively small size and high speed of the vessels under investigation; regarding Bravo unit, the enhanced stability characteristics may increase susceptibility to this failure mode. For the two loading conditions, both Alpha and Bravo units' outcomes in terms of vulnerability are basically similar.

Overall, the results indicate that vulnerability levels are generally consistent across failure modes, except for the DS failure mode. This issue has also been recognized in other application cases in the literature [16].

The application of the OL related to the Central Mediterranean Sea area has been carried out. This yields more severe outcomes than the initial assessment. However, the final classification of each unit as vulnerable or not vulnerable remains unchanged. In conclusion, it appears that for the investigated units, no design domain (in terms of vessel draft and VCG) exists that allows compliance with all stability failure modes simultaneously.

Finally, it should be noted that the SGISc represents an innovative tool for evaluating stability performance in waves. However, it is important to mention that the SGISc was developed and calibrated primarily for vessels longer than 24 meters. Therefore, the acceptability thresholds the results provided by criteria are compared with, may not be appropriate for the two units under investigation. Nevertheless, it is to be stressed again that the criteria are physically based and therefore in principle suitable. The added value of this investigation therefore could be the possibility to compare the two units: in this perspective Bravo unit appears to provide better performance.

References

[1] IMO. MSC.Resolution 267(85) - Adoption of the International Code on Intact Stability. 2008; London, UK.

[2] Belenky V., Bassler C.C. and Spyrou K.J. Development of Second Generation Intact Stability Criteria. Hydromechanics Department Report. 2011, Naval Warfare Center – Carderock Division, USA.

[3] US Coast Guard. Continued development of Second Generation Intact Stability criteria. 2019; Carderock Naval Architecture Division, USA.

[4] IMO. MSC.1/Circular 1627 - Interim Guidelines on the Second Generation Intact Stability Criteria. International Maritime Organization. 2020 Jan; London, UK.

[5] IMO. MSC.1/Circular 1652 – Explanatory Notes to the Interim Guidelines on the Second Generation Intact Stability Criteria. International Maritime Organization. 2023 Apr; London, UK.

[6] Shin D and Chung J. Application of dead ship condition based on IMO second-generation intact stability criteria for 13 K oil chemical tanker. Ocean Engineering 2021; 238:109776. DOI: 10.1016/j.oceaneng.2021.109776 .

[7] Petacco N, Pollicardo A and Gualeni P. An insight about roll damping within the second generation intact stability criteria. Journal of Ocean Engineering and Marine Energy 2024 Sep; 10:1011-1021. DOI: 10.1007/s40722-024-00347-9 .

[8] Petacco N, Ruggiero V and Gualeni P. Intact stability assessment of RO-RO pax vessel in the framework of Second Generation Intact Stability criteria with a specific focus on the operational profile. In: Progress in Marine Science and Technology 6 - Technology and Science for the Ships of the Future. 2022, Genoa, Italy. DOI: 10.3233/PMST220008 .

[9] Szodza S, Krata P. Towards Evaluation of the Second Generation Intact Stability Criteria - Examination of a Fishing Vessel Vulnerability to Surf-Riding, Based on Historical Capsizing. Ocean Engineering 2022 Mar; 248:110796. DOI: 10.1016/j.oceaneng.2022.110796 .

[10] Shigunov V. Direct stability assessment: Pragmatic solutions. Ship Technology Research 2017; 64(3): 144-162. DOI: 10.1080/09377255.2017.1392074 .

[11] Wandji C, Shigunov V, Pipiras V and Belenky V. Benchmarking of direct counting approaches. Ocean Engineering 2024 Mar; 296:116649. DOI: 10.1016/j.oceaneng.2024.116649 .

[12] Yang S.H. Study on the Parametric Rolling of Medium-Sized Containership Based on Nonlinear Time Domain Analysis. In: Proceeding of the 39th International conference on Offshore Mechanics and Arctic Engineering (ASME 2020). 2020.

[13] Petacco N, Petkovic G and Gualeni P. An insight on the post-processing procedure of the Direct Stability Assessment within SGISC. Ocean Engineering 2024 Apr; 305:117982. DOI: 10.1016/j.oceaneng.2024.117982 .

[14] Petacco N. An alternative methodology for the simplified operational guidance in the framework of second generation intact stability criteria. Ocean Engineering 2022 Sep; 266:112665. DOI: 10.1016/j.oceaneng.2022.112665 .

[15] Rinauro B, Begovič E, Gatin I, Jasak H. Surf-riding Operational Measures for Fast Semidisplacement Naval Hull Form. In: Proceedings of the 12th Symposium on High Speed Marine Vehicles (HSMV 2020) 2020 Nov; 5:219. IOS Press.

[16] Bulian G. and Orlandi A. Operational measures in second generation intact stability criteria: Effect of source of environmental data. In: Proceedings of the 1st International Conference on the Stability and Safety of Ships and Ocean Vehicles (STAB 2021) 2021 June; Glasgow, UK.

[17] Petacco N., Ruggiero V. and Gualeni P. An Investigation about Stability in Waves of Large Pleasure Yachts. Journal of Marine Science and Engineering 2023 Oct; 11:2039. DOI: 10.3390/jms11112039 .