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Second generation intact stability criteria: Application of operational limitations and guidance to a megayacht unit

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ABSTRACT: Second Generation Intact Stability criteria (SGISc) are under finalization at IMO aiming to provide a set of not mandatory criteria covering phenomena related to intact stability in waves. SGISc introduce also operational guidance and/or operational limitations to the navigation. The former entails the analysis of operational data (e.g. speed and headings) as complementary aspects to the ship design strategies. Operational limitations consist of restrictions to the environmental conditions or geographical area where the vessel may sail. This paper focuses on the operational guidance and limitations as proposed at the 7th session of IMO Ship Design and Construction sub-committee. An overview of the current rules concerning the operational aspects of the criteria is given. A comprehensive assessment of a mega yacht unit is carried out for the excessive accelerations phenomena, except for the direct stability assessment. Results are going to be presented with special attention to the operational aspects.

1 INTRODUCTION

In the latest ten years, the development of the so-called Second Generation Intact Stability Criteria (SGISc) has been addressed by the Sub-Committee on Safety Design and Construction (SDC) at the International Maritime Organization (IMO). As stated in the introductory parts of Intact Stability code (IMO 2008), the perceived need of new criteria able to assess the ship stability waves is at the origin of this activity. Therefore, the SDC sub-committee decided to tackle this issue with an innovative framework and considering the physically based approach as the leading principle. Four different phenomena have then been identified:

- Righting arm variation problems due to waves (parametric roll and pure loss of stability);
- Stability under dead ship condition;
- Maneuvering-related failures in waves (surf-riding/broaching-to);
- Excessive lateral acceleration.

The physics at the basis of this phenomena has been widely studied in literature. A comprehensive description of all the stability failure modes is given in Belenky et al. (2011) and in U.S. Coast Guard (2019).

An innovative method to tackle the SGISc, namely the multi-layered approach, has been proposed in 53/3/5 (2010). In the latest years the proposal has been modified and improved, the last version of the multi-layered approach is given in SDC 7/5/1 (2019). For each stability failure mode, three different assessment levels have been formulated, each one with an increasing level of accuracy. The assessment of Level 1 (LV 1) is very simple and fast to be carried out, but it give conservative results; on the other hand, assessment of Level 2 (LV 2) requires more information and calculations effort, even if the outcomes are more accurate. Finally, the Direct Stability Assessment (DSA) represents the third assessment level and it is the most accurate but also the most computational time consuming. This tool, in principle, should be based on non-linear time domain seakeeping numerical simulations, and it should be able to consider directly the coupling factors among selected ship motions involved in each stability failure addressed. As a supplementary level, some operational restrictions could be introduced in the assessment. These measures are divided in two categories: restrictions acting only on the environmental condition where the ship is supposed to sail, namely Operational Limitations (OL), and restrictions acting on the vessel operability such as headings and speeds in relation to the environmental condition encountered, i.e. Operational Guidance (OG).

At the beginning of criteria development, levels are intended to be carried out sequentially from LV1 to DSA passing trough LV2, but during the 5th session of SDC it has been clarified that no hierarchy among levels exists. It means that, even if the sequential application of vulnerability levels appears the most rational path to tackle the SGISc, there is no need to approach them with a hierarchical procedure. Therefore, ship designers may carry out the assessment by applying any level regardless the conservativeness adopted. The same applies also for OG and OL, which can be

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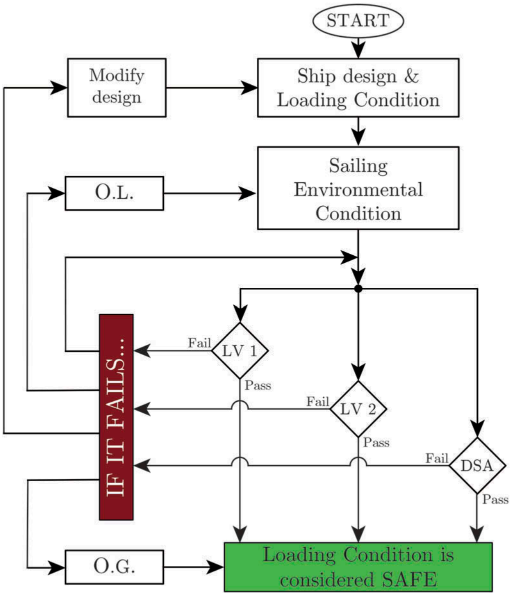

Figure 1. Simplified scheme of the application logic of second generation intact stability criteria.

carried out even before LV1 or LV2. A simplified schematization of the multilayered approach and its application logic is shown in Figure 1.

The finalized draft of Interim Guidelines for the application of all vulnerability levels, OG and OL has been presented at the SDC 6th session (SDC 6/WP.6 2019) and it is expected that SGISc will enter into force during 2020 for a trial period. For the time being, these new criteria should be treated as a supplementary assessment tool, in order to give a further guide to ship designers to assess ship stability under different aspects. An exhaustive overview about the steps that lead to the development of SGISc has been made by francescutto(2019).

In this paper, a focus on the OG and OL for the excessive acceleration phenomenon, as proposed at the 7th session of SDC by the intersessional correspondence group, is given (SDC 7/5 2019). An overview of the current rules concerning the operational aspects of the criteria will be given. Besides, an assessment of a mega yacht unit with the SGISc will be carried out, except for the third level. Results are going to be presented, when applicable by means of polar diagrams, and analyzed with special attention to the operational aspect that such set of rules can imply.

2 OPERATIONAL MEASURES IN THE SGISC FRAMEWORK

Although a more and more accurate ship design may increase notably the safety level of vessels, it is recognized that operational measures are required as a complementary tool to fully address the safety performance (Liw°ang 2019, Baˇckalov et al. 2015). In particular, this aspect assumes more relevance when complex phenomena related to navigation are addressed, such as those tackled by the SGISc. It is obvious that phenomena which are not controllable by human active role are excluded, for example the dead ship condition. Moreover, when too many restrictions to a loading condition are introduced by the operational measures, it means that this loading condition should not be deemed as acceptable in principle. Operational measures may be divided in two categories, depending on which sailing factor they treat: the environment where the vessel is sailing or the operational ship features.

2.1 *Operational guidance*

Operational Guidance may be considered as an additional vulnerability level able to identify which situations should be avoided. The assumed situation is defined as the combination of the sailing condition (V_S and μ) and the sea state characteristics, i.e significant wave height H_S, zero-crossing wave period T_Z, wind direction and gust characteristics. For this reason, OG could be considered as an independent tool able to evaluate ship stability in a seaway condition. A schematic representation of the operational guidance structure is proposed in Figure 2.

OG provides a set of information about the ship handling in specified sea state condition. With reference to vessel speed and heading, the guidance determines which actions should be carried out by the master in order to reduce the stability failure probability. Since the OG are drawn up during the design phase, it should embrace all the possible environmental conditions that might be encountered during the ship life. For this reason, detailed sea state and wind forecast information are required on board during the navigation, to allow the master to plan the best sailing condition (i.e. combination of ship forward speed V_S and mean wave encounter direction μ) according to the OG. Within the SGISc three equivalent approaches to draw up OG are provided:

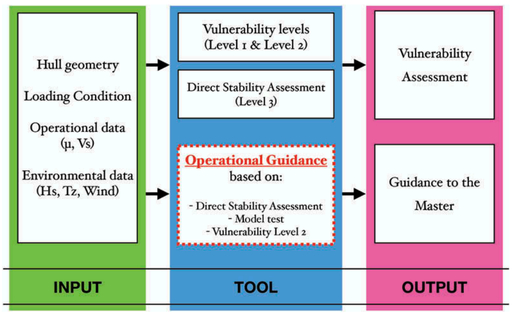

Figure 2. Scheme of operational guidance structure. It is considered as an independent assessment tool based on numerical simulation, model test or vulnerability assessment level.

– Probabilistic operational guidance;
– Deterministic operational guidance;
– Simplified operational guidance.

The simplified approach is based on the same methodology of LV1 and LV2, while the probabilistic and the deterministic approaches may share the same numerical calculation method of DSA. The numerical method should reproduce ship motions in irregular seas and should detect the failure event, defined as the exceedance of a specific roll angle or a lateral acceleration. The roll angle threshold is set equal to the minimum angle among 40 [deg], the vanishing angle or the downfloading angle evaluated in calm water. The threshold for lateral acceleration is set equal to gravity acceleration $g = 9.81$ [m/sec^2]. Moreover, lateral acceleration should evaluated at the highest position where crew or passengers may be present. Depending on the stability failure investigated, the numerical tool should replicate at least three degrees of freedom in the time domain, considering coupling factors among motions. Detailed technical requirements of the numerical tool are given in (SDC 7/5 2019). The development of a comprehensive numerical tool able to comply with the SGISc requirements is a challenge among experts and researchers, therefore great efforts have been made in this field (Shigunov et al. 2019, Kuroda et al. 2019)in the last years.

2.1.1 *Probabilistic operational guidance*

This kind of approach takes into consideration a probabilistic criteria, such as the probability of stability failure over a time period or the stability failure rate. For each loading condition, the allowed sailing condition are those for which the criterion does not exceed a corresponding probabilistic standard threshold. The relation between criterion and the standard is given in ((1)).

$$r < 10^{-6} \tag{1}$$

where r $[1/\text{sec}]$ is the upper boundary of 95% confidence interval of the stability failure rate.

The probabilistic approach requires that the numerical simulation proceeds until a failure event occurs, i.e. the exceedance of roll angle or lateral acceleration threshold. The duration of the simulation is used to calculate the failure rate. The criterion r is evaluated as the average over all the numerical simulations that have been carried out.

2.1.2 *Deterministic operational guidance*

This approach results to be faster than the previous one. It takes into account a deterministic criteria, such as maximum roll amplitude evaluated in a given exposure time. This simplification leads to a lower level of accuracy compared to the previous approach, therefore the standard threshold is conservatively selected, pursuing an equivalent level of safety. For a given loading condition, a sailing condition is deemed safe by this approach if ((2)) is observed.

$$\alpha \cdot X_{3\mathrm{h}} < X_{\mathrm{lim}} \tag{2}$$

where $\alpha = 2$ is a scaling factor to provide an equivalent safety level, $X_{3\mathrm{h}}$ is the mean-three hour maximum amplitude of roll angle or lateral acceleration while X_{lim} is the stability failure event threshold, i.e. roll angle or lateral acceleration.

The deterministic criterion may be calculated either using numerical simulation, models test or their combination. It is recommended that tests or numerical simulations have at least an overall duration of 15 hours for each combination of V_S, μ and environmental condition. There is the possibility to split the test or simulation into several part, not shorter than three hours.

2.1.3 *Simplified operational guidance*

Finally, simplified operational guidance represents the simplest but also the less accurate approach to draw up OG. In principle, simplified operation guidance may consist in any approximated conservative estimation method that has been proven to provide a superior conservative level compared to design assessment requirements, for example first and second vulnerability levels. Design assessments correspond to the application of LV2 or DSA.

Within the guidelines on SGISc, examples of recommended approach based on LV1 or LV2 are suggested. Briefly, these examples are summarized below:

– For pure loss of stability failure mode, it is suggested to avoid forward speed greater than $0.752 \cdot \sqrt{L_{PP}}$ [m/sec] in following to beam wave directions for those sea states not complying with LV2.
– For parametric rolling failure mode, forward speeds not compliant with second check of LV2 should be avoided in each wave directions for the considered sea states.
– For surf-riding/broaching failure mode two examples are provided. The first one suggests to avoid forward speed greater to $0.94 \cdot \sqrt{L_{PP}}$ [m/sec] in quartering seas for selected wavelength and wave height. The second approach is based on a modified version of LV2 taking into account diffraction wave forces; the critical speed obtained by the modified criterion should be avoided in following to beam seas for the considered sea state.
– For excessive acceleration failure mode, navigation is not recommended for those sea states not compliant with the modified LV2. The criterion modification introduces the waves encounter direction within the lateral acceleration Response Amplitude Operator (RAO) as well as the encounter wave frequency is considered.

2.2 *Operational limitations*

Operational Limitations set restrictions to the ship operability in the considered loading condition in terms of specific sea state or geographical area. Therefore, the OL may be considered as a tool acting directly on the environmental input data of another methodology in the framework of SGISc, such as vulnerability levels, DSA or OG. This is possible thanks to the modularity of the SGISc structure, mainly based on the physics behind the phenomena. In fact, criteria have been thought with the possibility to easily introduce modifications in the boundary conditions or in specific formulations. A schematic representation of the logical application of operational limitations is proposed in Figure 3.

According to how OL affects the environmental conditions, two typology of restrictions may be identified: related to the navigation areas or related to wave characteristics.

The first limitation defines specific operational areas, either geographical or typology (i.e. sheltered water), routes or specific year periods where the navigation is forbidden because of the high risk of stability failure. The environmental data can be modified acting on the selection of the appropriate wave scatter table, where the joint probability of the range of average zero-crossing wave period and significant wave height is reported, together with wind statistics. Since the OL related to areas or routes and season refer to fixed environmental condition, it is not required that detailed weather forecasts are present on board.

The restriction related to wave characteristics defines for which wave heights the risk to experience a failure event during the navigation is deemed acceptable. The OL related to maximum significant wave height modifies the wave scatter table used for the assessment. Sea states having a wave height higher than the selected one are cut off, obtaining a limited scatter table. These limitations are strictly related to the encounter sea conditions, thus it is necessary to have on board detailed weather forecast, inclusive of significant wave height. An interesting application of OL have been carried out by rudakovic:opLim.

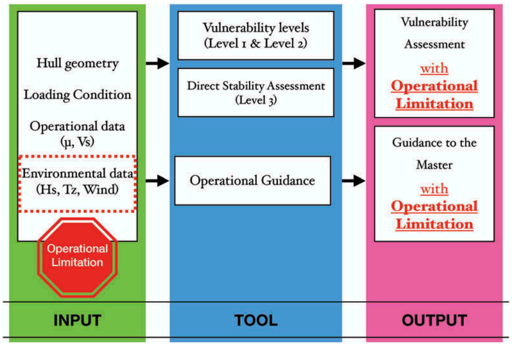

Figure 3. Scheme of logical application of the operational limitations. It acts on the environmental input data of the assessment tool in the SGISc framework, such as vulnerability levels, direct stability assessment or operational guidance.

3 APPLICATION CASE

In this paper, the vulnerability assessment of the excessive acceleration failure mode of a representative mega-yacht unit has been carried out. Main dimensions of the hull and the design loading condition are given in Table 1.

Excessive accelerations criterion requires the definition of the vertical and longitudinal coordinates of the highest location where crew or passengers may be present. In this analysis, the point has been located on the Sun Deck at 15.70 [m] from the keel line and its longitudinal relative position (with reference to the ship length) is 0.40 [-], as shown in Figure 4.

Initially, KG limiting curves have been evaluated for both LV1 and LV2. This first analysis has been carried out by means of an *in-house* computational codes, developed at the University of Genoa by Coraddu et al. (2011) and Petacco (2019). Thereafter, OL have been applied to the second vulnerability level and KG limiting curves have been computed again. Restrictions take into account both OL related to maximum significant wave height and OL related to geographical area. In the first application of limitations, four different limited scatter tables have been made starting from the full scatter table of North Atlantic ocean (IACS 2001). Maximum significant wave heights from 1.5 [m] to 15.5 [m], with steps of 2.0 [m], have been chosen to define the limited scatter tables. The second restriction consists in replacing the North Atlantic wave scatter table, defined by the criterion, with the Mediterranean wave scatter table. Wind statistics have been kept the same as those defined by the criterion.

Table 1. Hull dimensions and loading condition of the investigated mega-yacht unit.

Main dimension and Loading conditions		
L_{PP}	64.94	[m]
B	13.20	[m]
D	7.50	[m]
d	3.30	[m]
V_S	17.4	[kn]
KG	5.50	[m]
GM	1.91	[m]
T_{roll}	8.35	[sec]
C_B	0.562	[-]
C_m	0.918	[-]

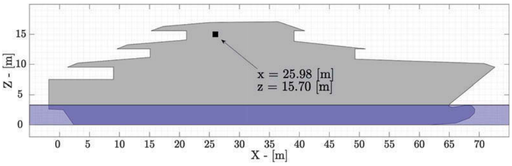

Figure 4 . Identification of the highest location where crew or passengers may be present on the longitudinal view of megayacht unit.

To complete the analysis, OG has been drawn up. In particular, simplified operational guidances have been evaluated for all the sea states contained within the North Atlantic scatter table. For sake of convenience, only a selection of representative polar diagrams have been reported in the following section.

In the next section, results will be shown in terms of KG limiting curves and polar diagrams and commented paying attention also to the operational aspect that such measures can imply.

4 RESULTS

Results of the excessive acceleration criteria application are shown in Figure 4. On the horizontal axis the assessed draught range is reported, while the limiting KGs are represented on the vertical axis. Because of the physics behind the excessive acceleration failure mode, the plotted curves should be considered as minimum limiting curves, i.e. the allowed domain is above the curve. This means that a loading condition is considered not vulnerable to the stability failure mode if the KG is located above the line. In the figure the limiting curves are represented, referring to the first vulnerability criterion and the second vulnerability criteria with and without OL. In the analysis, both typologies of limitations have been applied, i.e relating to the navigation areas and relating to the wave characteristics. For the first limitation, the North Atlantic wave scatter table has been replaced by the wave scatter table of Mediterranean sea (dash-dot line). The second restriction consists of cutting the North Atlantic scatter table up to a maximum significant wave height (dashed line). An allowed significant wave height equal to 7.5 [m] (the same of the maximum wave height of Mediterranean sea) has been set in order to consistently compare the two typologies of limitation. The Intact Stability code has also been applied and its maximum KG limiting curve is represented by a black line. This upper limit has been calculated according to the analysis of the righting lever curve properties (paragraph 2.2 of the Intact stability code) and it represents the maximum value of KG after which the unit fails to comply with the Intact Stability code.

In the analysed draught ranges, the limitation on the maximum wave height is the least conservative allowing the maximum design domain. On the contrary, as expected, the most conservative assessment is represented by the LV1 criterion, located in the upper part of the graph. Moreover, it appears that no design domain between Intact Stability code and LV1 curves exists for draught lower than 3.2 [m]. On the other hand, LV2 and OL limiting curves ensure a sufficient region where the unit may be designed.

With reference to the design loading condition (black cross), it appears that the vessel does not meet the requirements of the two vulnerability levels. In fact, the loading condition marker is located far below the LV1 and LV2 limiting curves. Therefore, to comply with the SGISc, the OL should be applied: the loading condition is still not compliant even if the restriction on the sailing area is applied; the introduction of a limitation on the maximum wave height permits to made the loading condition compliant with SGISc.

In Figure 6, the relationship between the minimum KG and the limiting significant wave height

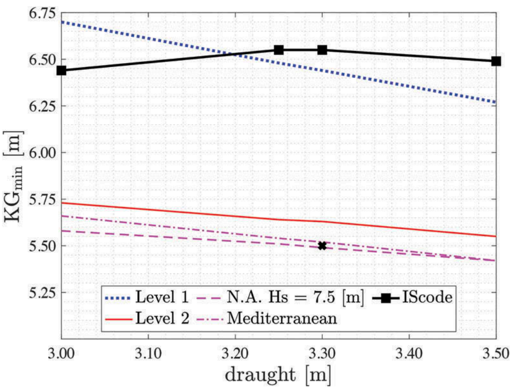

Figure 5. KG minimum limit curves for EA, both typologies of OL have been applied.

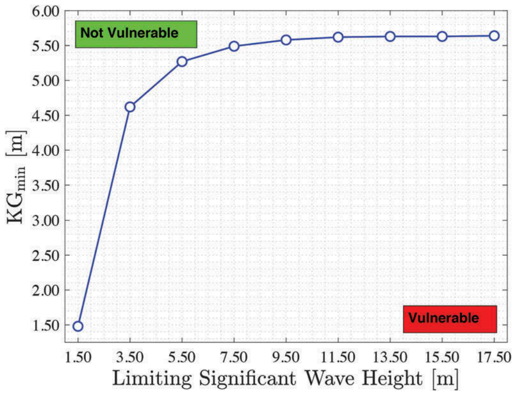

Figure 6. Relationship between the selected limiting significative wave height and the minimum allowed KG for EA.

for the excessive accelerations failure mode is shown. On the vertical axis, the minimum KG allowed by the application of OL is reported . The selected limiting wave height is reported on the horizontal axis: Hs equal to 17.5 [m] represents the North Atlantic full wave scatter table. Figure 6 shows how the minimum KGs are affected by the selection of the maximum significant wave height in OL. It seems that choosing limiting wave heights from 7.50 [m] up to 17.5 [m], i.e. the full wave scatter diagram of North Atlantic, affects slightly the limiting KGs. Below the limiting wave height equal to 7.5 [m], the minimum KG curve falls down quickly enlarging the design domain.

As concern the OG, the simplified methodology proposed SDC 6/WP.6 (2019), has been applied. Results have been presented by means polar plots. In the plots, heading seas direction is equal to 0 [deg] while following seas have a direction of 180 [deg]. Ship speeds are reported in knots along the radius of the graphs. Conditions that should be avoided, according to the simplified OG for the excessive accelerations failure mode, are indicated by red areas. To carry out a complete analysis and draw up the OG to the master, all the sea states within the wave scatter diagram should be assessed. The North Atlantic scatter table consists of 272 different sea states, 197 of which have a weighting factor different from zero. Due to the large amount of combinations between significant wave height and zero-crossing wave period, only polar diagrams for a limited selection of sea states are presented in this paper. Sea states having a zero-crossing wave period T_z close to the ship natural roll period are shown in Figure 7. Significant wave heights ranges from 3.5 [m] to 9.5 [m] with a step of 2.0 [m]. As expected, the higher the wave height, the larger the red area to be avoided become. It is interesting to see how forward ship speed affects vessel vulnerability to the failure mode: even if beam seas are deemed the worst sailing condition when referring to the excessive acceleration failure mode, Figure 5 shows that at higher speeds the vessel seems not to be vulnerable for the considered sea state.

5 CONCLUSIONS

An overview of the operational measures defined in the framework of SGISc has been given. Two main categories of restrictions are defined by SGISc: operational guidance and operational limitations. The first category is meant as an independent tool able to assess vessel vulnerability to a certain stability failure mode for assumed situations. Both environmental condition (sea state and wind statistics) and sailing condition (V_S and μ) are taken into account in the OG. On the other side, the second category, i.e. Operational Limitations, is able to act directly on the environmental conditions; thus OL should be always associated to another methodology in order

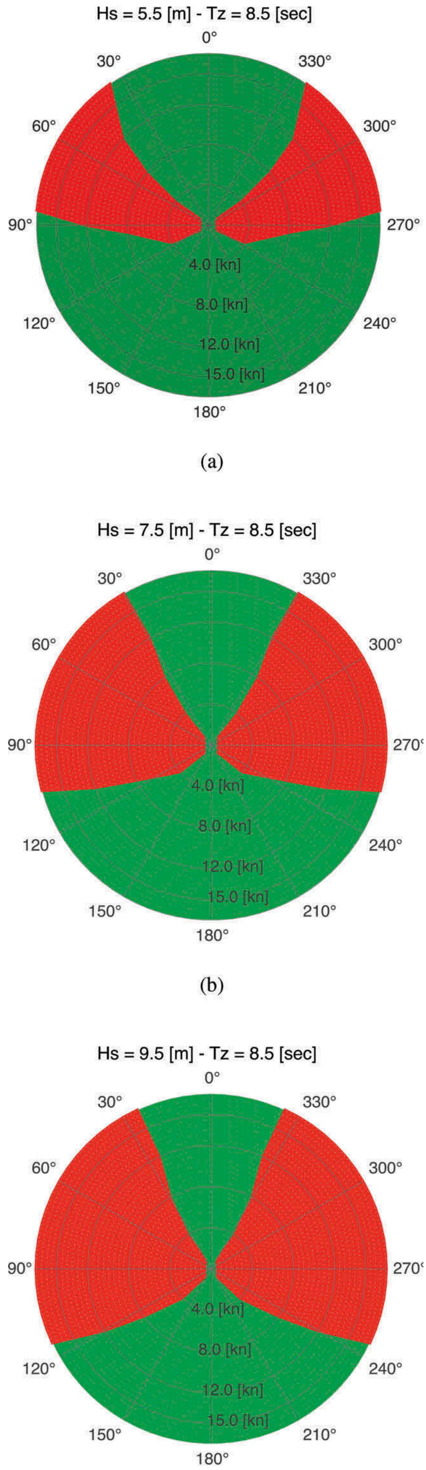

Figure 7. Representation of polar diagrams for a selection of sea states.

to assess the vulnerability of the vessel. According to the typology of the restriction made, OL can be classified as a limitation on the maximum wave height or a limitation to the operative geographical area.

An application of both typologies of OL and simplified OG for the excessive acceleration failure mode has been carried out. A representative megayacht unit has been investigated. Since the design loading condition is considered vulnerable by LV1 and LV2, it has been decided to apply both OL typologies of restriction. The design loading condition has been considered not vulnerable by changing the North Atlantic scatter table with the Mediterranean sea table. Moreover, outcomes show the high strictness of LV1, in fact taking into account the Intact Stability code limiting curve, it appears that for low values of draught no design domain exists. As concerns LV2, its limiting curve is located far below the Intact Stability curve allowing a sufficient design area for each draught investigated.

Then, an application of the simplified OG is presented. OG should be performed for each sea state listed in the wave scatter table, in this investigation for 197 cases. As expected, polar plots point out that the higher the wave height, the larger the forbidden operational area. Moreover, it is interesting to appreciate the effect of the sailing condition on the vulnerability judgement, e.g. for some wave heights in beam seas, even if this is the worst environmental condition for the excessive acceleration failure mode, the vessel is not considered vulnerable when sailing at high speed. This might be due to the influence of roll damping, in particular of the lift component. Nevertheless, it is worth to note that sailing at the maximum speed in certain sea states is not always practicable. Therefore, although a sailing condition improves the safety level in terms of stability, this may lead to a weakening of safety of other ship design aspects, such as seakeeping, longitudinal or local strength of structures.

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