Application of Second Generation IMO Intact Stability Criteria to Medium – Sized Fishing Vessels

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Abstract: In this work, a sample application of the draft criteria proposed in SLF 55/WP.3 for assessing pure loss of stability, parametric roll and broaching failure modes to medium sized fishing vessels, is presented. The sampled vessels consist of seven ships, including trawlers, longliners and purse – seiners, with lengths between 20 and 70 meters. This sample can be representative of the mid – sized Spanish current fishing fleet, including ships with quite different operative profiles and which are supposed to be safe from the static stability point of view (as they all comply with Torremolinos Protocol Requirements). On them, both loss of stability and parametric roll level 1 and 2 checks and broaching level 1 check have been carried out, analyzing the vulnerability of the different typologies to the three failure modes. Moreover, some comments regarding the applicability of these criteria to these types of ships and their use as a design tool to improve fishing vessels safety are included.

Key words: Second generation intact stability criteria, parametric roll, pure loss of stability, fishing vessels stability.

1. Introduction

Fishing is one of the industrial sectors with a higher number of fatalities, ranking between the most dangerous activities in many countries, such as the U.S., the U.K. or Spain [1]. Most of the accidents affecting the Spanish fleet of medium – sized vessels are due to stability issues (large heel and capsizing), usually due to reduced initial stability levels and crew lack of training in these matters. However, it is also well known that dynamic stability issues which affect this type of ships, such as parametric roll, broaching or loss of stability in stern seas, are not covered by any mandatory criteria. In addition, the ship tendency to being affected by one of these phenomena is not usually analyzed at any stage of its design.

The objective of the second generation intact stability criteria, is to set up methods which are aimed at evaluating the vulnerability of ships to some failure modes, mainly related to the aforementioned dynamic stability, which are not covered by existing criteria. Five are the failure modes under consideration, including loss of stability in stern seas, parametric resonance, broaching, dead ship condition and excessive accelerations.

These criteria, for each of the failure modes, follow a three-layer structure; the first one includes simple and easy to calculate criteria. If the ship fails to pass this first layer, a second one has to be evaluated, where a more accurate evaluation is proposed. Finally, if the vessel is considered as vulnerable under these two levels, a direct stability assessment is proposed, consisting on carrying out a detailed analysis of the ship behavior in the different sailing conditions and developing operational guidelines.

Work underdone in the last years in the SLF Sub - Committee of the IMO, which mainly began in 2005 during the 48th session of the SLF, involved the study and development of the requirements for each of the failure modes. An overview of the process could be found in [2]. In the SLF 55th session in 2013, agreement on pure loss of stability, parametric roll, broaching and dead ship stability modes was obtained

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[3], although some points remained undecided. Excessive accelerations criteria were still not defined.

Although considered within then, second generation criteria are mainly focused on cargo and passenger vessels and not on fishing vessels. In fact, most of the applicability studies include only a few vessels of this type (three vessels in [4] and [5], two in [6]). One characteristic of the fishing fleet is its vast heterogeneity, as their typology largely changes depending on the fishing equipment and also depending on the geographical location under analysis (due to the existent regulatory framework and design tradition in that area). This fact makes it very difficult to generalize the obtained results for a small sample to the different typologies and locations.

The main objective of this work is to carry out a sample application of the current draft of the second generation stability criteria (contained on SLF 55/WP.3 [7]) to Spanish medium/large sized fishing vessels, in order to analyze its applicability and its possible use as a design tool to improve the fleet safety. The failure modes under consideration are pure loss of stability, parametric roll and broaching.

The sampled vessels are representative of the medium/large sized Spanish current fishing fleet. It includes ships with quite different operative profiles, and which are supposed to be safe from the static stability point of view (they all comply with Torremolinos Protocol requirements, in force in Spain for all fishing vessel of more than 12 meters). Moreover, some additional information regarding the dynamic behavior in waves of some of the vessels is also available, which can contribute to the analysis of the applicability of the criteria.

On all of them, both loss of stability and parametric roll Level 1 and 2 checks and broaching Level 1 check have been carried out, analyzing the vulnerability of the different typologies to the three failure modes.

2. Sample Vessels

The Spanish fishing fleet ranks first in terms of tonnage among all the UE countries, and it is composed by nearly 10.000 vessels [8]. From these, more than 540 vessels have lengths of more than 24 meters, and more than 900 have lengths of between 20 and 24 meters [9]. The fleet is divided mainly in seven vessel types: medium sized fresh trawlers, large freezer trawlers, medium sized coastal purse seiners, large tuna purse seiners, medium sized long liners and large freezer longliners and finally medium sized fixed fishing gear vessels.

This study has been performed on a series of fishing vessels representative of the aforementioned fleet, including two medium-sized trawlers, one large freezer trawler, one longliner, one medium sized purse seiner and one large tuna purse seiner. In addition, and for the sake of comparison, the well known TS trawler has been also included in the sample, although its arrangement doesn´t follow the Spanish standards.

From the above described vessels, towing tank tests in different conditions are available for a medium sized trawler [10,11] (named Trawler 2 in this work) and for the TS vessel [12].

Moreover, as fixed fishing gear vessels usually operate in coastal and protected waters, and its number is not very large, they have been excluded from this analysis.

The main characteristics of the analyzed vessels are included in Tables 1 and 2.

2.1 Tested conditions

In all cases, and in order to obtain a more conservative result, ships have been considered not to be equipped with bilge keels. Moreover, design speed has been the one considered in all cases to compute the reference ship speed (V_{PR}).

Table 1 Vessel characteristics (1)

Vessel	L_{Pp} (m)	B (m)	d (m)	C_b
Trawler 1	25,70	8,50	3,25	0,56
Trawler 2	29,00	8,00	3,30	0,57
Large Trawler	60,60	12,50	4,60	0,54
Longliner	24,00	8,20	3,20	0,68
Purse Seiner	21,00	7,00	2,70	0,67
Tuna Purse Seiner	67,60	14,00	4,80	0,53

TS Trawler (d_1)	22,00	6,90	2,30	0,47
TS Trawler (d_2)	22,00	6,90	2,46	0,48

Table 2 Vessel characteristics (2)

Vessel	L/B	B/D	D/d
Trawler 1	3,02	1,51	1,73
Trawler 2	3,63	1,38	1,76
Large Trawler	4,85	1,63	1,66
Longliner	2,93	1,41	1,81
Purse Seiner	3,00	2,19	1,19
Tuna Purse Seiner	4,83	1,54	1,90
TS Trawler (d_1)	3,19	2,06	1,46
TS Trawler (d_2)	3,19	2,06	1,36

Finally, regarding the loading conditions under analysis, the design draft has been the one considered. In the cases in which the real sailing conditions of the ship were available, the minimum GM of the different conditions has been selected for testing. Moreover, an additional IMO minimum required GM value of 350 mm has been also tested in these cases. For those ships with unknown sailing situations, the minimum required GM value for complying with the IMO Torremolinos Protocol (350 mm), has been considered.

3. 2nd Generation Intact Stability Criteria

As it has been already mentioned, 2nd generation intact stability criteria present a three tier structure for all of the five failure modes.

Table 3 Tested Conditions

Vessel	Fn	d (m)	GM_T (m)
Trawler 1 LC1	0,32	3,25	0,653
Trawler 1 LC2	0,32	3,25	0.350
Trawler 2	0,31	3,30	0,350
Large Trawler	0,31	4,60	0.350
Longliner LC1	0,34	3,20	0,495
Longliner LC2	0,34	3,20	0,350
Purse Seiner	0,36	2,70	0,350
Tuna Purse Seiner LC1	0,34	4,80	0,916
Tuna Purse Seiner LC2	0,34	4,80	0,350
TS Trawler LC1	0,32	2,30	0,730
TS Trawler LC2	0,32	2,46	0,436

In this work, the Levels 1 and 2 of the draft proposal contained in [7] for parametric roll resonance and pure loss of stability failure modes, and Level 1 for broaching, has been applied. The obtained results are shown in the following sections.

3.1 Parametric Roll

Autoparametric roll resonance, parametric roll resonance or simplifying, parametric roll, could be defined as a ship dynamic instability. It is caused by the variation of ship transversal restoring capabilities when waves pass along the hull, together with the effects of the coupling between roll, heave and pitch motion. It reaches its largest intensity in head or stern seas, when wave height exceeds a given threshold and when ship-wave encounter frequency approximately doubles the ship roll natural frequency.

In these conditions, roll motions could increase rapidly up to very large amplitudes, leading, in the worst cases, to the capsizing of the vessel. The intensity of this phenomenon depends also on many other factors, such as ship hull forms, wave amplitude and frequency, roll damping, etc. Of course, the possible consequences that derive from one of these episodes depend on that intensity, but well known incidents have shown that these can be devastating.

Second generation criteria regarding parametric roll resonance are based on the analysis of *GM* variation in longitudinal waves of given values of wavelength and height.

The first level criterion is based on the comparison of the amplitude of the variation of metacentric height as a longitudinal wave of wavelength $\lambda = L$ and wave height $h = L \cdot S_W$ passes the ship (ΔGM), where S_W is a constant wave steepness of 0.0167, with the metacentric height in calm water (GM). Under this condition, the ship is considered vulnerable if:

$$\frac{\Delta GM}{GM} > R_{PR} \qquad (1)$$

Where R_{PR} represents roll linear damping, that may be taken as 0.5 or a value dependant on bilge keel area.

The second level is a two tier criterion. Regarding the first check, it is similar to that of the first level criterion; however, in this case *GM* variation is computed for a series of 16 different waves, and compared to the average *GM* on each of the wave cases, weighing the results according to a wave scatter database. Moreover, an additional requirement taking into account the effect of forward speed in the appearance of parametric roll is also considered. According to this first check, the ship will be considered vulnerable if:

$$C1 = \sum_{i=1}^{N} W_i C_i > R_{PR0} \quad (2)$$

Where *Wi* is the wave case weight and *Ci* is a coefficient equal to 1 if the ship is vulnerable under *GM* and speed checks, and 0 if not. *GM* vulnerability checks are the same as those of the first level criterion, but computed for each of the wave parameters. The ship is considered as vulnerable if:

$$GM(H_i, \lambda_i) < 0 \quad (3)$$

$$\frac{\Delta GM(H_i, \lambda_i)}{GM(H_i, \lambda_i)} > R_{PR} \quad (4)$$

The speed requirement consists on comparing the design speed of the ship (V_D) and a reference speed for parametric roll appearance (V_{PRi}), which depends on the metacentric height on waves and calm water, wave conditions and natural roll period. The ship is considered as vulnerable if:

$$V_{PRi} < V_D \quad (6)$$

Finally, the second check has a similar structure to the first check, and the vulnerability of the ship is evaluated obtaining the maximum roll motion of the ship in different head and stern longitudinal waves (306 cases), at different speeds, and by using an uncoupled equation of roll motion.

The ship, according to this two tier method, is considered not to be vulnerable if it complies with the first check or if it complies with the second check after failing the first one.

3.2 Pure Loss of Stability

Pure loss of stability failure mode is, as it happens with parametric roll resonance, caused by the effect of longitudinal waves passing along the hull, subsequently modifying waterplane area. This modification periodically alternates between wider and slender waterplanes (when a wave crest is situated in the ship bow and stern and amidships respectively), and is especially critical when wavelength is similar to ship length. The modification in flotation area implies a variation in transverse stability, which changes as wave passes along the hull.

Under these circumstances, when a ship sails in stern seas and spends time on the minimum stability condition (wave crest amidships), it may experience large roll angles and even capsizing if stability levels have been largely reduced due to the wave effect.

The pure loss of stability criteria are also divided into two levels. The first level criterion is based on the evaluation of the minimum value of the metacentric height as a longitudinal wave of wavelength $\lambda = L$ and wave height $h = L \cdot S_W$ passes the ship (GM_{min}), where S_W is the constant wave steepness, that in this case is 0.0334. Under this condition, the ship is considered vulnerable if:

$$GM_{\min} < R_{PLA} \quad (7)$$

where R_{PLA} is the minimum value between 0.05 m and a speed and draft dependant factor.

The second level check consists of three criteria (CR_j), computed for two possible set of waves (16 or 306 cases). Each CR_j is obtained by weighting the coefficients Cj_i, which are evaluated for each wave condition and that are equal to 1 if the angle of vanishing stability (φ_v) is over 30 degrees, the maximum loll angle (ϕ_{loll}) is over 25 degrees and if the maximum GZ value is under $8 \cdot (H/\lambda) \cdot d \cdot Fn^2$, respectively.

$$CR_{j=1:3} = \sum_{i=1}^{N} W_i Cj_i \tag{8}$$

So, the ship is considered to be vulnerable if:

$$\max(CR_1, CR_2, CR_3) > R_{PL0} \tag{9}$$

Where R_{PL0} is 0.06 for the first set of waves and 0.15 if the second option is adopted.

Pure loss of stability criteria are only applied to vessels with a Froude number exceeding a threshold value, still under consideration; the minimum of the different possibilities is 0.2.

3.3 Broaching

The phenomenon of broaching is caused by the effect of large stern waves acting on the ship, forcing it to travel at their own speed and generating a directional instability, which may lead to a large yaw motion and subsequent roll, while the ship deviates from its original course.

Broaching criteria is also divided in Level 1 and Level 2 tests. Level 1 is the same as that included in the IMO guidelines for avoiding dangerous situations in adverse weather (MSC.1 Circ. 1228), and stablishes a Froude number limit of 0.3. All ships sailing at speeds over this limit, are considered vulnerable to the broaching failure. Regarding level 2, a direct evaluation of the surf-riding sensibility of the ship is needed [3].

4. Application and Results

4.1 Parametric Roll

Regarding the evaluation of parametric roll vulnerability, both Level 1 criteria and Level 2 first check have been analyzed for all vessels. In all cases, no bilge keels have been considered; so, the Level 1 limiting factor R_{PR} has been taken as 0.5.

In Table 4, the results for Level 1 criterion are shown. On it, ΔGM represents the GM variation on the specified waves and ΔGM_{alt} represents the alternative GM variation in waves computed considering the waterplane inertias at drafts d_h and d_l [7].

In Table 5, the results for the first check of the Level 2 criterion are presented. On it, ΔGM_{max} represents the maximum GM variation for all the 16 wave cases, GM_{avg} is the corresponding average GM for that wave case and V_{PR} is the reference ship speed for resonance in that conditions.

As can be seen in Table 4, all ships pass the Level 1 criterion except the largest ones, and in the case of the Tuna Purse Seiner, the criterion is not fulfilled only in the minimum GM condition.

Regarding the Level 2 test, all vessels pass the criteria for all wave cases and positions along the hull, obtaining a *C1* value of 0.

The criteria, for the sampled ships, are consistent, and none of the vessels found vulnerable under Level 1 requirements, was classified as vulnerable under Level 2.

Table 4 Parametric roll. Level 1 results

Vessel	ΔGM (m)	ΔGM_{alt} (m)	$\Delta GM/GM$	Level 1
Trawler 1 LC1	0,090	0,164	0,251	Pass
Trawler 1 LC2	0,090	0,164	0,468	Pass
Trawler 2	0,102	0,133	0,379	Pass
Large Trawler	0,109	0,251	0,718	Fail
Longliner LC1	0.051	0.062	0.126	Pass
Longliner LC2	0,051	0,062	0,178	Pass
Purse Seiner	0,035	0,046	0,130	Pass
Tuna Purse Seiner LC1	0,154	0,295	0,322	Pass
Tuna Purse Seiner LC2	0,153	0,295	0,843	Fail
TS Trawler LC1	0,095	0,205	0,281	Pass
TS Trawler LC2	0,107	0,181	0,414	Pass

Table 5 Parametric roll. Level 2 results. 1st check

Vessel	ΔGM_{max} (m)	GM_{avg} (m)	$\Delta GM_{max}/GM_{avg}$	V_{PR} (m/s)	Level 2
Trawler 1 LC1	0,075	0,650	0,115	1,186	Pass
Trawler 1 LC2	0,073	0,347	0,211	2,040	Pass
Trawler 2	0,085	0,353	0,241	0,728	Pass
Large Trawler	0,104	0,360	0,287	1,707	Pass
Longliner LC1	0.044	0.495	0.089	1.110	Pass
Longliner LC2	0,045	0,349	0,128	0,935	Pass
Purse Seiner	0,034	0,352	0,097	1,171	Pass
Tuna Purse Seiner LC1	0,152	0,895	0,169	2,090	Pass
Tuna Purse Seiner LC2	0,152	0,330	0,460	3,069	Pass
TS Trawler LC1	0,090	0,719	0,125	1,019	Pass
TS Trawler LC2	0,100	0,444	0,225	0,473	Pass

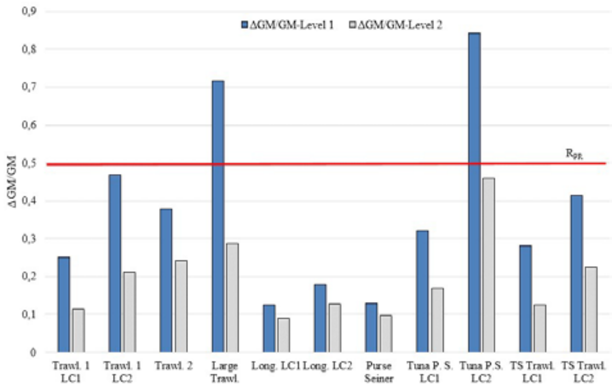

Fig. 1 – Parametric Roll Level 1 $\Delta GM/GM$ and Level 2 $\Delta GM_{max}/GM_{avg}$

One remark has to be made regarding the cases of Trawler 2 and the well known TS Trawler. Both vessels have a very large tendency to developing parametric roll resonance, even in wave the conditions evaluated in Level 1 and 2 tests, as can be observed in [11] and [12] and the two vessels have been judged as non-vulnerable under Level 1 and 2 tests.

Related to this, one main common characteristic of fishing vessels may be highlighted. Their hull forms don´t usually present very pronounced bow flares, as could be the case, for example, of containerships or Ro Pax vessels, although in many occasions transom and overhanging sterns are present.

In addition, in some occasions, as shown in [13], the changes in *GM* with wave passing are very small by themselves, and heave and pitch motions have more influence for triggering roll resonance than *GM* variation. This can be appreciated in the results presented in the aforementioned tables, where the values of the ΔGM seem to be quite small in comparison, for example, to the results shown in [14] for other types of ships.

The fact that both criteria are based on the analysis of *GM* variation in waves under the balance of trim and heave on waves approach, where dynamic pitch and heave effects are not included, may be the cause of this results.

Regarding the tuna purse seiner, a comparison with one of the ships tested in [15] can be made. Both ships have similar dimensional relationships, coefficients and hull shape, and tests have shown that it is prone to capsizing in head waves of wavelength to ship ratio in the order of 1. Level 1 criterion seems to provide good agreement in this case.

If the different types of ships are compared, it can be concluded that trawlers and the large tuna purse seiner, are the ones more vulnerable to this failure mode. Two of them failed the stablished requirements, and the rest present the largest values of GM variation in waves among the ones fulfilling the criteria. The longliner and the purse seiner, with hull forms where little flare is present, are considered as non-vulnerable.

4.2 Pure Loss of Stability

In the case of pure loss of stability evaluation, the design speed have been chosen for all ships; in all vessels, Froude number is over 0.2, and so these set of criteria are of application. Level 1 and Level 2 tests have been carried out. Regarding Level 2 analysis, the option of 16 reference wave cases (Option A, [7]), instead of the 306 cases option, has been chosen.

In Table 6, the results for Level 1 criterion are shown. On it, GM_{min} represents the minimum GM as the specified wave passes the ship and GM_{min_alt} represents the alternative minimum GM computed considering the waterplane inertia at draft d_L [7].

In Table 7, the results for the Option A of the Level 2 criterion are presented. On it, GZ_{max} represents the minimum smallest GZ curve maximum for all the 16 wave cases, φ_v and ϕ_{loll} are respectively the vanishing stability and loll angles for that condition and R_{PL3} is the vulnerability limit for the presented GZ_{max}.

Table 6 Pure loss of stability. Level 1 results

Vessel	GM_{min}	GM_{min_alt}	Level 1
Trawler 1 LC1	0,452	0,488	Pass
Trawler 1 LC2	0,148	0,184	Pass
Trawler 2	0,172	0,075	Pass
Large Trawler	0,193	-0,147	Fail
Longliner LC1	0.391	0.342	Pass
Longliner LC2	0,246	0,197	Pass
Purse Seiner	0,276	0,231	Pass
Tuna Purse Seiner LC1	0,626	0,028	Fail
Tuna Purse Seiner LC2	0,060	-0,540	Fail
TS Trawler LC1	0,520	0,105	Pass
TS Trawler LC2	0,271	-0,113	Fail

Table 7 Pure loss of stability. Level 2 results. Option A

Vessel	GZ_{max}	φ_v	ϕ_{loll}	R_{PL3}	Level 2
Trawler 1 LC1	0,422	90	0	0,084	Pass
Trawler 1 LC2	0,199	70	0	0,085	Pass
Trawler 2	0,746	125	0	0,075	Pass
Large Trawler	0,187	51	0	0,115	Pass
Longliner LC1	0.392	82	0	0.088	Pass
Longliner LC2	0,293	73	0	0,089	Pass
Purse Seiner	0,269	78	0	0,086	Pass
Tuna Purse Seiner LC1	0,995	111	0	0,148	Pass
Tuna Purse Seiner LC2	0,451	95	0	0,136	Pass
TS Trawler LC1	0,254	70	0	0,056	Pass
TS Trawler LC2	0,144	58	0	0,060	Pass

In the case of pure loss of stability, the two vulnerable ships to parametric roll Level 1 are again vulnerable to pure loss of stability Level 1, although in this last case, the large tuna purse seiner is shown to be vulnerable in the two loading conditions under consideration. In addition, the TS Trawler, in one of its loading conditions, is also vulnerable according to the Level 1 test of this failure mode.

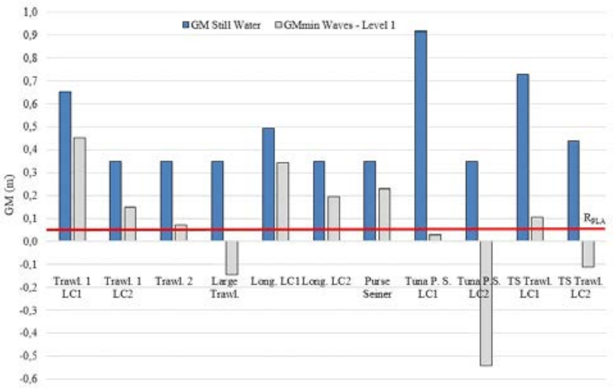

Fig. 2 – Pure loss of stability Level 1 minimum *GM* in waves and *GM* in still water

Again, as in the parametric rolling case, all vessels have been judged as non vulnerable under the Level 2 test, showing the consistency of the criteria.

In all wave cases and positions, all criteria have been fulfilled, and *C1*, *C2* and *C3* values are equal to 0.

Regarding the comparison of the obtained results with known data of the behavior of the tested ships, in [16] the tendency of the TS Trawler to capsizing in stern seas due to loss of stability is shown. In [15], it is shown that the purse seiner described in the previous chapter, is also vulnerable to this phenomenon.

Regarding the Trawler 2, it has been judged as non-vulnerable under both levels; in [17], the stability reduction in stern waves of this ship is demonstrated, although no capsizing is mentioned, as there is still a margin of positive stability.

According to this, it seems that pure loss of stability criteria could address the vulnerability of the type of vessels under analysis in a more accurate way than in the previous case, where pitch and heave have a larger influence on the behavior of the vessels.

Comparing the different typologies, again the trawlers and the tuna purse seiner are the most vulnerable ships, while both the longliner and the small purse seiner seem to be safe from the pure loss of stability failure point of view.

4.3 Broaching

Taking into account that all ships present a Froude number larger than 0.3, they are all classified as vulnerable according to Level 1 broaching criterion. In [18], it is shown that similar ships to those tested in this work have a large tendency to broaching. However, the analysis of Level 2 is needed to make any conclusions on this matter.

5. Conclusions

This work presented a sample application of the draft second generation intact stability criteria contained in the SLF55/WP.3 report, to a set of seven fishing vessels, which are representative of most of the typologies within the large Spanish fishing fleet.

The main objective of this work was to analyze the applicability of these criteria as a design tool that could improve the safety of the aforementioned vessels.

In order to do this, parametric roll resonance and pure loss of stability level 1 and Level 2 criteria, and broaching level 1 criterion, were applied to the 7 sample ships, considering a total number of 11 loading conditions.

As a first step, the consistency of the criteria was verified by checking that no discrepancy between Level 1 and Level 2 vulnerability results was found.

In a second step, the obtained results were analyzed, in order to determine the suitability of the criteria for evaluating the probability of the different types of ships of suffering the three phenomena, by comparing the obtained results with the known behavior of the different vessels.

Regarding parametric roll, only two vessels were vulnerable according to Level 1, and none according to Level 2. These two vessels were the largest of the sample. Some of the smaller ships, which are known for being prone to resonance, were qualified as safe under these criteria. Ships with small GM variation in waves, but with large amplitude pitch and heave motions, may have its vulnerability levels underestimated by these criteria.

Regarding pure loss of stability, three ships were found vulnerable under Level 1 test, and none according to Level 2. In this case, results show more consistency with the experimental data available for the different ships of the data base, and criteria seem to be applicable for all the different ship typologies.

With respect to broaching, all ships were judged as vulnerable according to Level 1 check.

From the results above, it can be concluded that the current draft version of the second generation intact stability criteria represents an easy to use tool for evaluating the possible vulnerability of medium sized fishing vessels. Its results show good agreement with realistic data of the analyzed vessels for the case of pure roll of stability. For the case of parametric roll, a more detailed analysis is needed for the case of small trawlers, where some discrepancies have been shown.

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