# Possibility of Capsizing of a 45-M Tuna Fishing Vessel According to IMO Second Generation Intact Stability Criteria

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***Abstract– Intact stability of a tuna fishing vessel was analyzed with the second generation stability criteria of the International Maritime Organization (IMO). Those criteria are being under development, and it was desired to compare these results with those from other references where numerical simulations were developed for the same vessel. Ship analyzed is a 44 m in length overall, which used to operate from Ecuadorian ports in Eastern Pacific Ocean. Unlike the current stability criteria, the new one considers ship response to the dynamic action of waves, in four capsizing modes, and consider several levels of vulnerability. If the calculations show that in a failure mode the ship is not vulnerable, the procedure continues to consider the next mode; but, if the ship does not satisfy the criterion, it must be checked at the next level of vulnerability. The fishing vessel was analyzed in two loading conditions, and it was found that according to this second generation stability criteria, it is not prone to capsize in Pure loss of stability, Parametric roll and Deadship condition. But it is vulnerable in the first two vulnerability criteria to Surfriding, phenomenon which likely will conduct to a sudden change in heading which would make the ship to capsize. These findings are consistent with the numerical simulations developed for the ship in two other references.***

***Keywords—surfriding, parametric roll, stability, fishing vessel.***

## I. INTRODUCTION

Possibility of fishing vessel capsizing takes this professional activity to be considered of high risk for its operators. Then for its operation at present the stability of a ship must be evaluated with the criteria established by the International Maritime Organization, agency dedicated to insure safe maritime transportation. However, in spite of these regulations, accidents occur like the Ecuadorian fishing vessel that in year 2014 sank at about 180 miles from the Galápagos islands, involving human losses, [1]. After two years of that accident another fishing vessel was affected around 220 miles from the port of Manta, Ecuador, [2]. It must be mentioned that the present IMO regulations consider only quasi-static calculations to evaluate stability.

In the Second Generation of Intact Stability Criteria (2GISC) IMO [3], is considering dynamics wave effects on the ship that may take her to capsize; in these regulations four capsizing or failure modes are analyzed. Two of them Pure loss of stability and Parametric roll are the result of reduction in metacentric height and to roll motion resonance, when the ship navigates in waves from bow or stern. Ship surfriding followed by an involuntary change in course may likely end in ship capsizing. Finally in the situation of Deadship, main power is lost which causes the ship to receive waves and wind from the beam, and, to reduce roll damping, all of which increase the possibility of capsizing.

For the stability evaluation being developed by IMO, different levels of analysis are developed, and for each one of the failure modes mentioned in the above paragraph. If it is determined that a mode is not likely to occur, then you have to proceed to analyze the next mode of failure, see Fig. 1. These criteria do not yet reach the category of mandatory by the international maritime community, but they have to contribute by testing this safety tool.

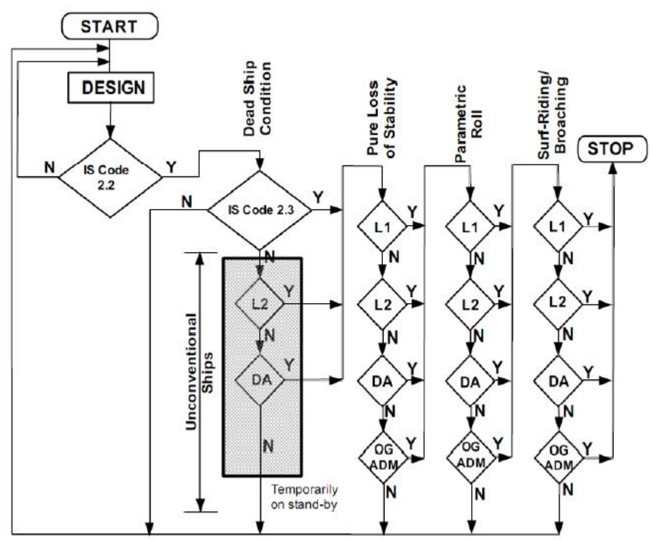


Fig. 1 Evaluation according to the Second Generation of stability criteria, [8].

There are several studies about the applicability of the 2GISC in fishing vessels. In Spain it was analyzed the applicability of those criteria, [4], but with exception of surfriding, it was concluded that criteria at level 1 were acceptable, but disagreeing in the applicability of level 2 for parametric balance and deadship. In the same country with a similar fishing fleet, it was analyzed the use of criteria for loss of propulsion, [5], concluding that it was needed new regulation for ships with low length.

In fishing vessels operating in the Pacific Ocean, between others numerical simulations were developed of two modes of failure for the same tuna fishing vessel which capsized, [6] and [7]. It was concluded that roll parametric resonance in irregular waves with a very small amount of damping resulted in very small amplitudes of oscillation; on the contrary in [7], when the ship receives regular waves from the stern, it was found possible that they capture the ship and force her to advance with them. In the present work the vulnerability of the four modes of failure of the mentioned fishing vessel will be analyzed applying the current version of the 2GISC. The objective is to determine if the numerical findings of previous work [6] y [7] are consistent with the new IMO criteria.

## II. Description of Fishing Vessel

### *A. Main characteristics and ship lines*

The tuna fishing vessel analyzed in this work is 44 meters in overall length. This vessel capsized around Galápagos archipelago in the eastern Pacific Ocean. The ship has a cargo capacity of 300 tons, and operated with a maximum velocity of about 12 knots, [7]. Her lines, Fig. 2, show double chine, with a deadrise angle of 15º and bulb at its bow:

TABLE I

Fishing vessel main characteristics

| Characteristic | Value | Units |
|---|---|---|
| Length overall | 44.03 | [m] |
| Length between perpendiculars | 39.8 | [m] |
| Breadth | 8.00 | [m] |
| Depth | 5.03 | [m] |
| Draft – design | 4.55 | [m] |
| Block coefficient | 0.65 | - |
| Main engine power | 1076 | [hp] |

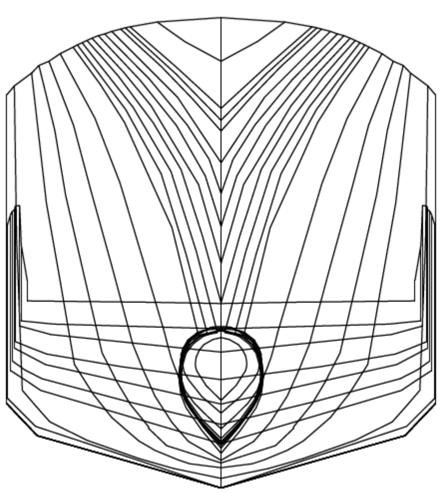

Fig. 2 Ship sections.

Following the general distribution plan of the ship is presented in Fig. 3.

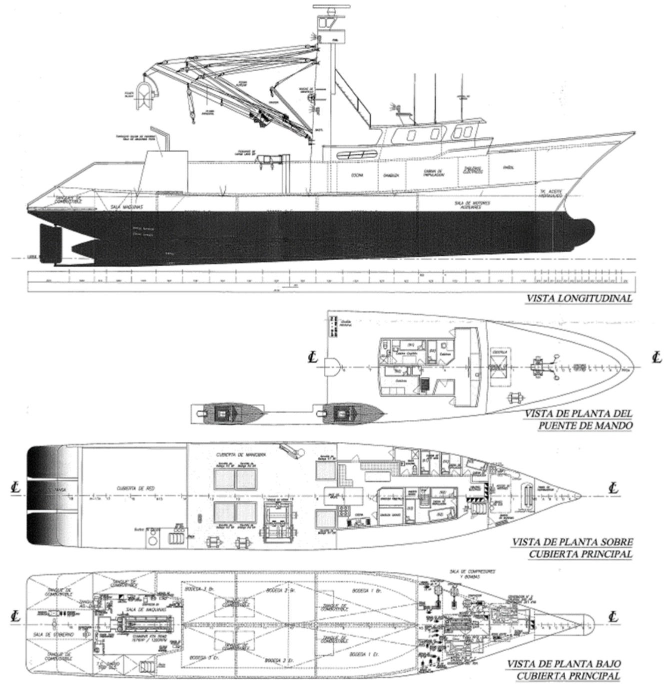


Fig. 3 General distribution plan.

For some calculations, it is necessary to have information on the propulsion characteristics of the vessel, shown in table II:

TABLE II

Fishing vessel propulsion characteristics

| Characteristic | value | units |
|---|---|---|
| Propeller diameter | 1.90 | [m] |
| Propeller pitch ratio | 0.73 | |
| Shaft power | 1000 | Hp |
| Developed area ratio | 0.60 | |
| Propeller blade number | 4 | |
| Propeller rational speed | 350 | rpm |
| Wake factor, *w* | 0.30 | |
| Thrust deduction factor, *t* | 0.23 | |

### *B. Loading conditions*

Two extreme load conditions are analyzed, ship leaving port and returning to port with tanks with full capture. In Table III, characteristics of each loading condition are presented. Results from the original inclining experiments are taken to estimate displacement and position of center of gravity of the ship in each loading condition.

TABLE III

LOADING CHARACTERISTICS

| Characteristic | Port departure | Return to port |
|---|---|---|
| Displacement, tons | 802.8 | 895.7 |
| Mean draft, m | 4.06 | 4.43 |
| Freeboard, m | 0.73 | 0.35 |
| Trim (+ aft), m | -0.17 | -0.22 |
| Long. Position of G (from Midships, +fwd) | -2.41 | -2.49 |
| Vertical position of G, m | 3.62 | 3.51 |
| Metacentric height, $GM_T$, m | 0.44 | 0.57 |

### C. *Ship resistance*

Some of the calculations require estimations of ship resistance at different velocities. For this work 1984 Holtrop method [11] was applied, with the following results for the two loading conditions.

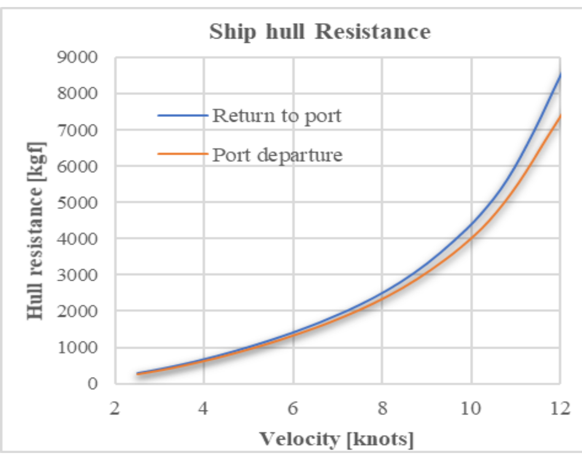


Fig. 4 Holtrop estimation of hull resistance.

## III. EVALUATION AT FIRST LEVEL OF VULNERABILITY

According to the IMO stability evaluation process, the four modes of capsizing must be checked at first level of vulnerability. Since the process is being reviewed previous to being accepted and implemented, evaluation at this level is to be completed following these references:

- Pure loss of stability: Annex 1, SDC 2/WP.4, 2015 [12]
- Parametric roll: Annex 2, SDC 2/WP.4, 2015 [12]
- Surf-riding: Annex 3, SDC 2/WP.4, 2015 [12]
- Deadship: Annex 1, SDC 3/WP.5, 2016 [10]

In the 2GISC, influence of wave profile on static stability parameters is frequently considered. In figures 5 and 6, metacentric height as function of wave height at different positions of wave crest along the length of the ship are shown. In port departure, Fig. 5 negative metacentric heights are obtained from wave height of 8% of ship length. In contrast in the port arrival condition, Fig. 6, metacentric height basically stays in positive side. For both loading conditions, reduction is noticeable when wave crest is around 0.6-0.7 of length from the forward end. This is typical, since in this case forward and aft end ship sections present a large reduction in beam, and therefore in waterplane inertia.

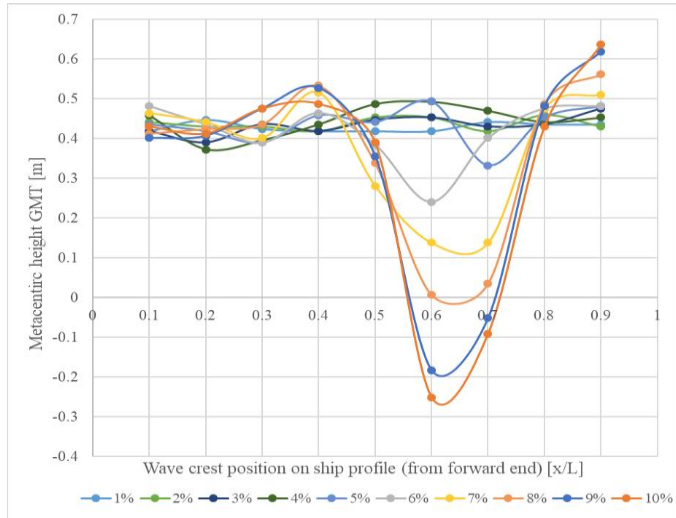


Fig. 5 $GM_T$ in waves as function of wave crest position, port departure

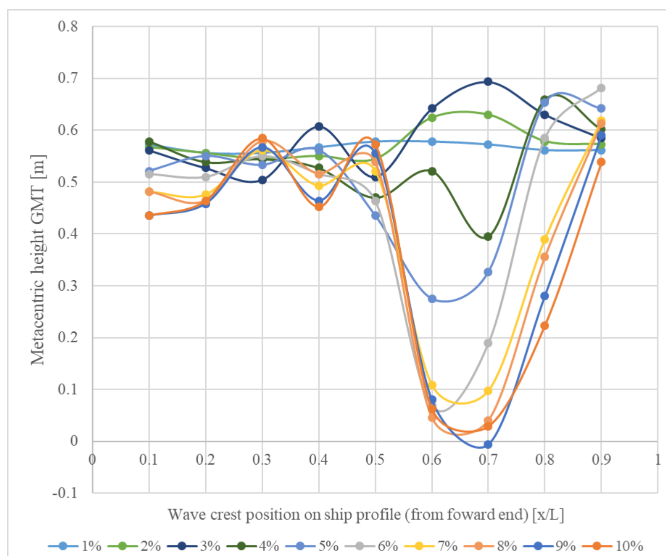


Fig. 6 $GM_T$ in waves as function of wave crest position, port arrival

### B. *Pure loss of stability*

A ship is not vulnerable to Pure loss of stability if her metacentric height is larger than 0.05 m. To evaluate the minimum metacentric height ($GM_{min}$), there are two options, according to the following conditional:

$$\frac{V_D - V}{A_w(D-d)} \geq 1 \tag{1}$$

where $V_D$ is the hull volume up to main deck, in cubic meters, $V$ is the hull volume in the loading condition, both in cubic meters, $A_w$ is the water plane area in square meters, $D$ is depth and $d$ is draft in the loading conditions, both in meters. If the previous relation is satisfied, then minimum metacentric height is calculated with the following:

$$GM_{min} = KB + \frac{I_L}{V} - KG \tag{2}$$

Water plane inertia is calculated at a lower draft, $d_L$, than the one in the loading condition:

$$\delta d_L = min(d - 0.25 d_{full}\ , 0.5\ S_w\ L)\ ;\ S_w = 0.0334 \tag{3}$$

$$d_L = d - \delta d_L\ ;\ I_L = f(d_L) \tag{4}$$

If relation (1) is not satisfied, the minimum value of metacentric height is calculated considering waves with the following characteristics and crest positions. Wave length equal to ship length, wave height $h$ equal to $0.0334L$, and position of the wave crest, from forward end: iL, i=1, 2, …, 9.

In relation (2), waterplane inertia must be included in the calculation, and to simplify the process, this parameter is interpolated from values at different drafts, with a 5th order polynomial.

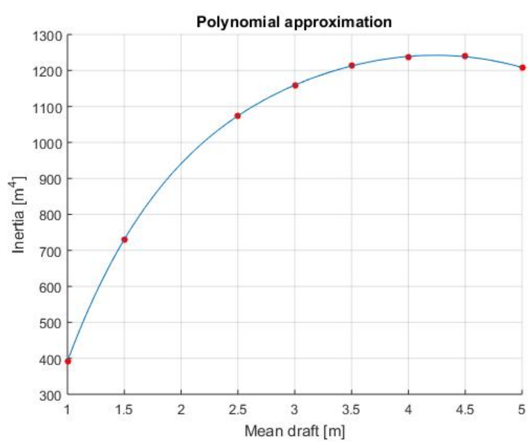


Fig. 7 Interpolation of waterplane inertia.

In case relation (1) needs to be applied, metacentric height may be estimated interpolating the righting arm curve for small angles of heel (0-10º). Polynomial employed is 2nd order, and the $GM_{min}$ corresponds to the minimum value considering different positions of wave crest along the length of the ship.

Results of these calculations are shown in table IV.

TABLE IV
EVALUATION OF PURE LOSS OF STABILITY

| **Load condition: port departure** | | | 1 |
|---|---|---|---|
| ***($V_d$-V)/$A_w$(D-d)>=1*** | *Min draft, $d_L$* | | 3.39 m |
| | *Inertia for min draft, I ($d_L$)* | | 1205.62 m$^4$ |
| | ***$GM_{min}$*** | | *0.389 m* |
| ***($V_d$-V)/$A_w$(D-d)<1*** | *Wave length, λ* | | 42.11 m |
| | *Wave height, H* | | 1.41 m |
| | ***$GM_T$ (λ, H)*** | *0.9 L* | 0.453 m |
| | | *0.8 L* | 0.441 m |
| | | *0.7 L* | 0.435 m |
| | | *0.6 L* | 0.481 m |
| | | *0.5 L* | 0.481 m |
| | | *0.4 L* | 0.424 m |
| | | *0.3 L* | 0.395 m |
| | | *0.2 L* | 0.413 m |
| | | *0.1 L* | 0.435 m |
| | ***$GM_{min}$=min($GM_T$)*** | | *0.395 m* |
| ***$V_d$-V/$A_w$(D-d)*** | | | 0.992 |
| ***$GM_{min}$*** | | | **0.395 m** |
| **Not vulnerable if *$GM_{min}$*>= 0.05 m** | | | **Not vulnerable** |

In the following figure, variation of metacentric height is shown for both loading conditions, which shows that minimum values are well above the required one. In consequence, this ship is not expected to be prone to this mode of failure. Similar result is found for the second loading condition.

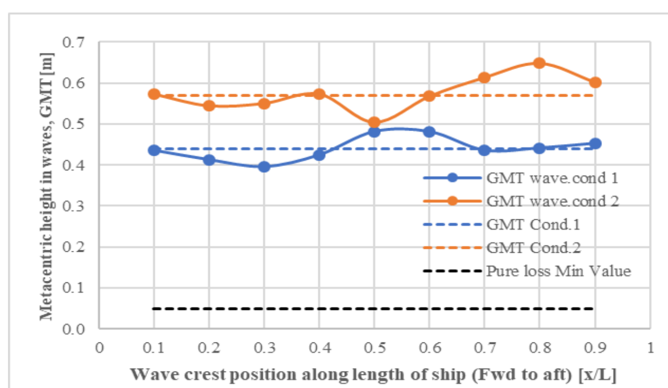


Fig. 8 Variation of $GM_T$ with wave crest position

## C. Parametric roll

A ship is considered not vulnerable to parametric roll at first level, if satisfies the following condition, where $R_{PR}$ is a parameter calculated based on midship section area coefficient, and projected area of bilge keel:

$$\frac{\Delta GM_1}{GM_T} \geq R_{PR} \tag{5}$$

The proposed rule by IMO requires to calculate the change in mean metacentric height ($\Delta GM_1$) as the wave profile travels along ship length. To do this, conditional (1) previously employed in the evaluation of Pure loss of stability is applied. Following methodologies to calculate mean metacentric height is explained.

If relation (5) is satisfied, change in $GM_T$ is calculated with the difference in water-plane inertia with higher and lower drafts than in the load condition analyzed ($d_H$ and $d_L$). These drafts are evaluation with equations (6) and (7).

$$\Delta GM_1 = \frac{I_H - I_L}{2V} \tag{6}$$

$$\delta d_L = min\left(d - 0.25 d_{full}, 0.5 S_w L\right);$$
$$\delta d_H = min\left(D - d, 0.5 S_w L\right);\ S_w = 0.0167 \tag{7}$$

Once these changes in draft are calculated, waterplane inertia at these new drafts are interpolated:

$$d_H = d + \delta dH\ ; d_L = d - \delta d_L\ ;\ I_H = f(d_H);\ I_L = f(d_L) \tag{8}$$

If relation (5) is not satisfied, inertia of waterplane is taken as half of the difference between maximum and minimum values in waves. Wave length is taken equal to ship length and wave height h is equal to 0.0167$L$. Wave crest positions are taken at: $iL, i= 1, 2, \ldots 9$, measured from forward end.

Results of the evaluation are shown in Table V for condition 1. In both loading conditions the results are similar, and the ship is considered not vulnerable in this mode of failure.

TABLE V
EVALUATION OF PARAMETRIC ROLL

| Loading condition: port departure | | | 1 |
|---|---|---|---|
| $V_d$-$V/A_w(D-d)$>=1 | Min draft, $d_L$ | | 3.74 m |
| | WP inertia at $d_L$ | | 1231.14 $m^4$ |
| | Max draft, $d_h$ | | 4.44 m |
| | WP inertia at $d_H$ | | 1241.53 $m^4$ |
| | **$\Delta GM_T$** | | 0.007 m |
| $V_d$-$V/A_w(D-d)$<1 | Wave length, $\lambda$ | | 42.11 m |
| | Wave height, $h$ | | 0.70 m |
| | $GM_T$ ($\lambda$, $H$) | 0.1 $L$ | 0.447 m |
| | | 0.2 $L$ | 0.441 m |
| | | 0.3 $L$ | 0.407 m |
| | | 0.4 $L$ | 0.424 m |
| | | 0.5 $L$ | 0.441 m |
| | | 0.6 $L$ | 0.441 m |
| | | 0.7 $L$ | 0.441 m |
| | | 0.8 $L$ | 0.435 m |
| | | 0.9 $L$ | 0.430 m |
| | $\Delta GM_T=(max(GM_T)-min(GM_T))/2$ | | 0.020 m |
| $V_d$-$V/A_w(D-d)$ | | | 0.992 |
| **$\Delta GM_T$** | | | **0.020 m** |
| **$\Delta GM_T/GM_T$** | | | **0.046** |
| **$R_{PR}$** | | | **0.170** |
| **Not vulnerable if $\Delta GM_T/GM_T$<=$R_{PR}$** | | | **Not vulnerable** |

## D. Surfriding and broaching

Evaluation at level I of this mode of failure is based in Froude number. Ship is considered not vulnerable in this mode of capsizing if the Froude number is low:

$$Froude\ number: Fn = \frac{0.514 V_s}{\sqrt{Lg}} \leq 0.3 \tag{9}$$

where $V_s$ is ship velocity in knots, $L$ is the waterline length, and $g$ is gravity acceleration. If the ship travels with a very low velocity is very difficult for a wave train to capture the ship and force her to surf.

For a vessel length of 42.11 meters, and a velocity of 12 knots, Froude number is 0.303. So this ship is considered prone to this type of failure, at this level of evaluation.

## E. Deadship

When a ship loses power, her velocity is null, and the damping coefficient in roll diminishes; also, waves move the ship so they start impacting from the side, with maximum excitation moment in roll. The evaluation of this mode of failure coincides with the meteorological criterion of IMO, in the calculation of a parameter $s$ that depends on the natural period of roll.

Meteorological criterion considers quasi-static action of the wind which produces a heel angle $\varphi_o$ . After the ship receives a wind gust, it is supposed that a wave train acts in the opposite direction, which produces a heel angle of $\varphi_1$ in the ship. In this inclined situation the vessel has potential energy to heel the ship, which corresponds to area $a$ in Fig. 9. The criterion compares this with the area below the righting arm curve area $b$, which opposes the capsizing. If the second area is larger than $a$, the ship is considered not vulnerable in this mode of failure.

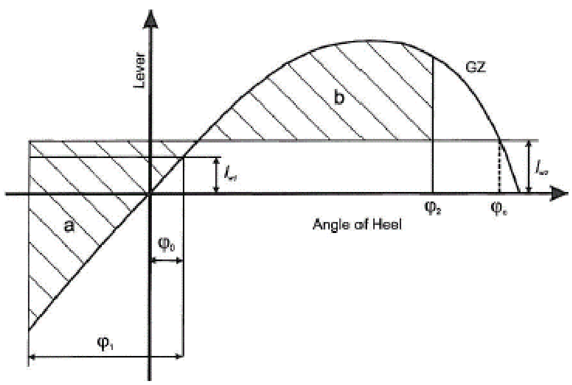


Fig. 9 Evaluation of meteorological criterion, [9]

For the integrations of area below righting arm curve, a fifth order polynomial is developed, see Fig. 10. To estimate the metacentric height, the slope at the origin is calculated with values of righting arm $GZ$ for heel angles below 10°.

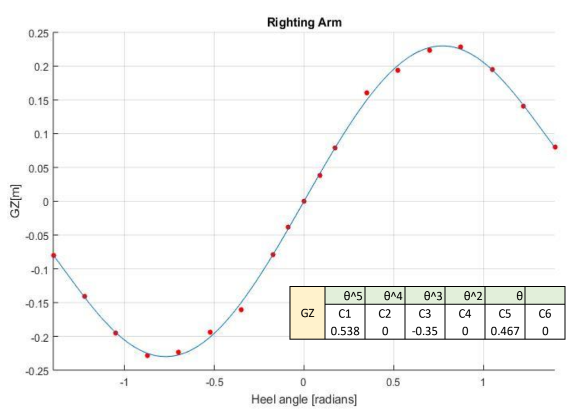


Fig. 10 Fifth order polynomial approximation of righting arm curve, [13]

Following in Table VI, results of this evaluation are shown for loading condition 1, which are similar to those in the second one.

TABLE VI
EVALUATION OF DEADSHIP CONDITION

| Loading condition: port departure | | 1 |
|---|---|---|
| $lw_1$ | | 0.08 m |
| $lw_2$ | | 0.13 m |
| $\varphi_0$ | | 10.5 [°] |
| $V_d$-$V/A_w(D-d)<1$ | $k$ | 0.7 |
| | $X_1$ | 0.75 |
| | $X_2$ | 0.915 |
| | $r$ | 0.661 |
| | $T$ | 7.951 sec. |
| | $s$ | 0.093 |
| | $\varphi_1$ | 13.0 [°] |
| $\varphi_2$ | | 50.0 [°] |
| **Area *a*** | | **0.023 m-rad** |
| **Area *b*** | | **0.044 m-rad** |
| **Not vulnerable if *area b >= area a*** | | **Not vulnerable** |

### F. *Summary of results at level I of vulnerability*

Applying IMO second generation stability criteria this ship is not vulnerable to capsizing modes: Pure loss of stability, Parametric roll, and, Deadship. But since the Froude number of the ship is greater than 0.30, it is vulnerable to Surfriding and Broaching, and must be checked in more detail at level II of vulnerability.

## IV. EVALUATION OF SURFRIDING AT VULNERABILITY LEVEL II

### A. *Introduction*

Following the scheme proposed by IMO Fig. 1, if a ship fails to satisfy evaluation at first level of vulnerability, it must be checked at level II of that mode of failure. In this case this ship must be evaluated in Surfriding. References employed for this calculation from the Subcommittee on Ship Design and Construction (SDC) of IMO are:

- Regulations for vulnerability level II of Surfriding: Annex 3, SDC 2/WP.4, 2015 [12]
- Corrections of vulnerability level II of Surfriding: General, SDC 3/WP.5, 2016 [10]
- Explanatory notes for vulnerability level II of surfriding: Annex 5, SDC 3/WP.5, 2016 [10]

To evaluate the possibility of capsizing at level II in the surfriding mode, it is necessary to evaluate certain factors named $C_{2ij}$. In the pertinent IMO regulations these calculations are named Analytic section. In the following step, named Probabilistic, a parameter $C$ is obtained using weighting factors depending on the possibility of finding waves with different characteristics, and also on factors $C_{2ij}$.

### B. Analytic section

Regulation uses the coefficient $C_{2ij}$, using the conditional (10), dependent on the service Froude number of the ship ($F_n$) compared with a critical Froude number ($F_{ncr}$) that is calculated in the regular wave characteristics (wave to ship length ratio, $s_i$ and, wave steepness, $r_j$):

$$C_{2ij} = \begin{cases} 1 & si \quad Fn > Fn_{cr}(r_j, s_i) \\ 0 & si \quad Fn \le Fn_{cr}(r_j, s_i) \end{cases} \quad (10)$$

where $F_{ncr} = u_{cr} / \sqrt{Lg}$ is the critical Froude number correspondent to the navigational surfriding limit calculated in regular waves, $r_i$, is the ratio wave to ship length ratio, varying from 0.03 until 0.15 with increments $\Delta r$=0.0012, $s_j$ is the wave wave steepness varying from 1.0 up to 3.0 with increment $\Delta s$=0.025, and, $u_{cr}$, is the critical velocity of the ship calculated from the following equilibrium relation (11), according to a propeller critical rotational velocity ($n_{cr}$) .

To determine coefficients $C_{2ij}$ as function of Froude number in waves with characteristics $s_j$ and $r_i$, it is necessary to find the critical velocity of the ship $u_{cr}$ solving the following equilibrium equation in the $x$-direction:

$$T_e(u_{cr}; n_{cr}) - R(u_{cr}) = 0 \quad (11)$$

where,

$R(u_{cr})$, is the ship resistance in calm water as function of $u_{cr}$,

$T_e(u_{cr};\ n_{cr})$, is the thrust developed by the propeller in calm water as function of $u_{cr}$ and $n_{cr}$, where in turn,

$n_{cr}$, is the propeller rotational velocity corresponding to the surfriding navigational limit.

To solve relation (11), it is necessary to calculate $n_{cr}$ using the following equation which includes the characteristics of the wave $s_j$ and $r_i$. In this equation wave characteristics and ship propulsion parameters are explicitly mentioned.

$$2\pi \frac{T_e(c_i, n_{cr}) - R(c_i)}{f_{ij}} + F(M, Mx,\ f_{ij}, k_i,\ c_i, \kappa_{0,1,2}, r_{0,1,2,3,4,5}) = 0 \quad (12)$$

where,

$M$, (kg) is the dry mass of the ship,

$M_x$, (kg) is the added mass of the ship ($\approx$10% of $M$),

$f_{ij}$, (N) is the force amplitude exerted by the wave on the ship hull,

$k_i = 2\pi / r_i L$ , (1/m) is wave number,

$c_i = \sqrt{g / k_i}$ , (m/s) is wave celerity,

$\kappa_{0,1,2}$ , are the coefficients of 2nd order polynomial interpolation of the thrust coefficient in calm water, and,

$r_{0,1,2,3,4,5}$ , are the coefficients of 5th order polynomial interpolation of ship resistance in calm water.

The amplitude of the force generated by the wave on the ship`s hull may be estimated with the following expression:

$$f_{ij} = 0.5 \rho g\, k_i H_{ij} \sqrt{Fc^2 + Fs^2}\ (N) \quad (13)$$

where,

$H_{ij} = s_j\, r_i\, L\ ,(m)$ is wave height,

$F_c$ and $F_s$ are the components of the Froude-Krylov force developed by the wave, which may be estimated by (m$^3$):

$$Fc = \sum_{i=1}^{N} \Delta x_i\ S(x_i) sin(k_i\ x_i) exp(-0.5 k_i\ d(x_i)) \quad (14)$$

$$Fs = \sum_{i=1}^{N} \Delta x_i\ S(x_i) cos(k_i\ x_i) exp(-0.5 k_i\ d(x_i)) \quad (15)$$

where,

$x_i$, (m) longitudinal position of $i^{th}$ ship section from midship (positive forward),

$D(x_i)$, (m) draft of $i^{th}$ ship section in calm water,

$S(x_i)$, (m$^2$) area of submerged $i^{th}$ ship section in calm water, and,

$N$, number of ship stations.

### C. Probabilistic section

According to the proposed IMO regulation a ship is not vulnerable in surfriding in this II level of analysis if parameter $C$ defined in equation (16) is less than 0.005. To evaluate this number values of the coefficients $C_{2ij}$ previously explained in the Analytic section are needed. Also, other weighting factors derived from frequency of wave trains are included:

$$C = \sum_{H_S} \sum_{T_Z} \left( W_2(H_S, T_z) \frac{\sum_{j=1}^{Ns_j} \sum_{i=1}^{Nr_i} W_{ij} C_{2ij}}{\sum_{j=1}^{Ns_j} \sum_{i=1}^{Nr_i} W_{ij}} \right) \quad (16)$$

In SDC 2 [12] the previous expression was proposed, but in the following year, in SDC 3 [10], it was slightly updated as follows. This is the version used in this work.

$$C = \sum_{H_S} \sum_{T_Z} \left( W_2(H_S, T_z) \sum_{j=1}^{Ns_j} \sum_{i=1}^{Nr_i} W_{ij} C_{2ij} \right) \quad (17)$$

where,
$W_2(H_s, T_z)$, is a weighting factor of the sea state in short term, as function of significative height and wave period (Fig. 11), and,
$W_{ij}$, is a statistic weight of each particular wave as function of $s_j$ and $r_i$, with a discretization of $Ns_j$ equal to 100 and $Nr_i$ to 80.

In reference [10] weighting factor $W_2$ is presented in tabular form. In this work those values are presented as a surface, Fig. 11, as function of wave height $H_s$ and average wave period $T_z$.

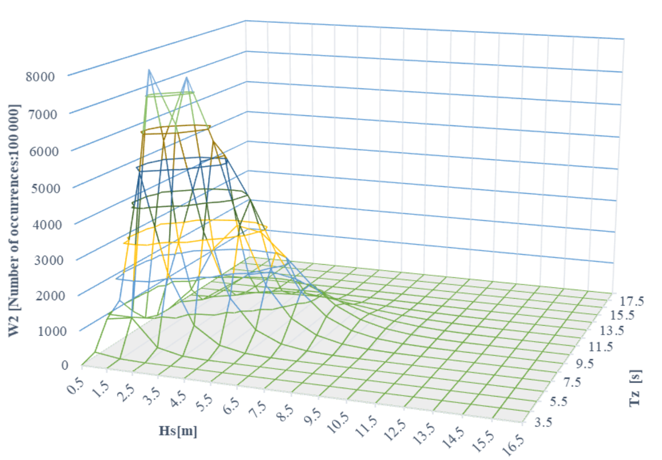

Fig. 11 Weighting factor for sea states in short term

The parameter $W_{ij}$ is evaluated by:

$$W_{ij} = \frac{4\sqrt{g}\; L^{5/2}\; T_{01}}{\pi\nu\; H_s^3} s_j^2 r_i^{3/2} \left( \frac{\sqrt{1+\nu^2}}{1+\sqrt{1+\nu^2}} \right) \Delta r\, \Delta s \, \bullet$$
$$exp\left[ -2 \left( \frac{L r_i s_j}{H_s} \right)^2 \left\{ 1 + \frac{1}{\nu^2} \left( 1 - \sqrt{\frac{g\, T_{01}^2}{2\pi\, r_i\, L}} \right)^2 \right\} \right] \quad (18)$$

where,
v, 0.4256,
$g$, acceleration of gravity,
$T_{01}$, (s) is equal to 1.086 $T_z$,
$T_z$, (s) average wave period, and,
$H_s$, (m) significative wave height.

*D. Results of calculation*

Thrust coefficient: To estimate this coefficient propeller is assumed to belong to the B-series. Then starting with the geometric characteristics, pitch ratio, expanded area ratio and number of blades, see values in Table II, $K_T$ is evaluated for several advance coefficient values ( $J = V(1-w)/(ND)$ ), and the interpolating polynomial may be completed, using the command `polyfit` of MATLAB, Fig 12.

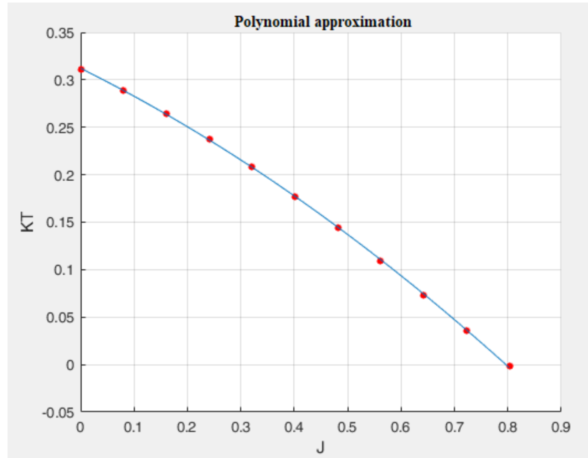

Fig. 12 Interpolation of propeller thrust coefficient

Wave force, $f_{ij}$.- This parameter is used to calculate critical rotational propeller speed. To complete this calculation sectional surface and drafts are required, and sine and cosine components of Froude-Krylov force are calculated, using equation (13).

Critical propeller rotational velocity ($n_{cr}$).- With the ship resistance, propeller thrust coefficient, wave force on the ship hull and wave celerity is possible to calculate critical rotational speed using equation (12). To do this, the mentioned equation is evaluated for different values of the rotational speed, and the critical value is found using the command roots from MATLAB. Figure 13 shows the intersection with the horizontal axis, corresponding to the critical value $n_{cr}$, of the propulsion system caused by the wave force on the hull.

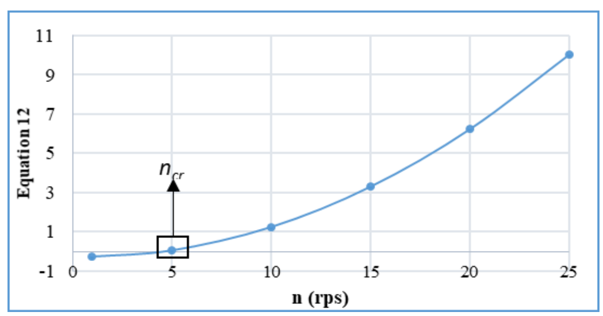

Fig. 13 Calculation of critical rotational velocity, $n_{cr}$

Ship critical velocity: after rotational critical velocity is obtained, ship critical velocity is calculated. This is done by equilibrating propeller thrust and ship resistance. In Fig. 14, it is shown the value of $u_{cr}$ where both functions coincide.

Calculation of $C_{2ij}$ coefficient: This parameter may value 0 or 1, see eqn. (10), and its distribution is shown in figure 15 for both loading conditions. It may be observed that for short waves, low $r_i$ values, possibility of surfriding increases with lower values of wave steepness.

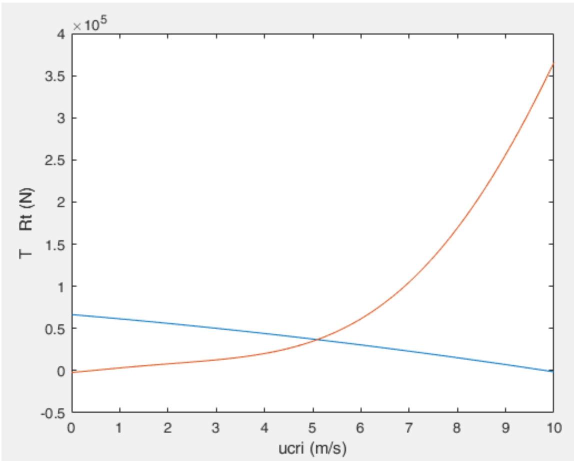


Fig. 14 Equilibrium between Propeller Thrust and Ship Resistance, [13]

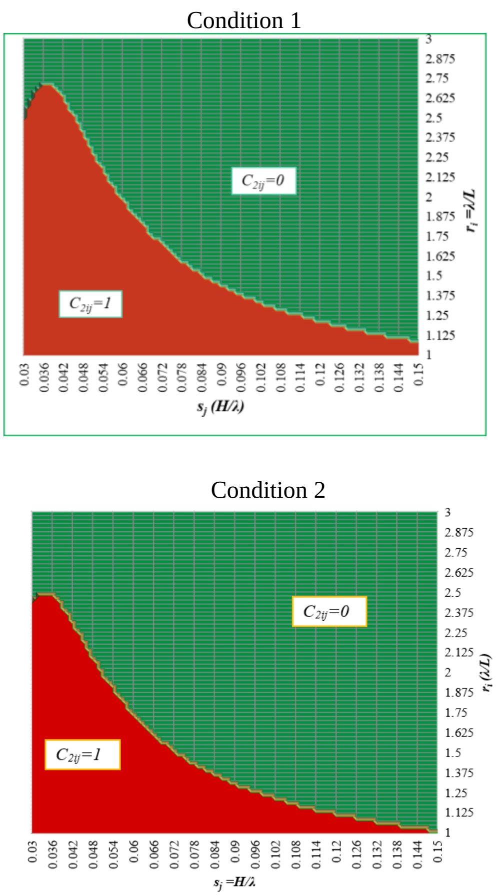


Fig. 15 Evaluation of coefficient $C_{2ij}$ for both loading conditions, [13]

With all information available, $C$ coefficient is evaluated. Table VII shows a summary of the calculation. In the first loading condition, the ship is vulnerable to this mode of failure, while in the second, she is not. But it must be notice that coefficient $C$ is very close to the limit.

TABLE VII
SURF RIDING SUMMARY RESULT, LEVEL II

| **Loading condition:** | | **1** | **2** |
|---|---|---|---|
| **Ship resistance polynomial interpolation coefficients** $R_t[N]=v^5r_5+v^4r_4+v^3r_3+v^2r_2+vr_1+r_0$ | $r_5$ | -6.90 | -8.39 |
| | $r_4$ | 165.96 | 221.99 |
| | $r_3$ | -739.84 | -1421.33 |
| | $r_2$ | 873.87 | 4763.76 |
| | $r_1$ | 5114.85 | -2548.48 |
| | $r_0$ | -2263.25 | 129.82 |
| **Propeller thrust coefficient interpolation polynomial coefficients** $K_T=J^2\kappa_2+J\kappa_1+\kappa_0$ | $\kappa_2$ | -0.1413 | -0.1413 |
| | $\kappa_1$ | -0.2795 | -0.2795 |
| | $\kappa_0$ | 0.3121 | 0.3121 |
| **Ship operation velocity, knots** | | 12.0 | 12.0 |
| **Coefficient** $C$ | | **0.0054** | **0.0048** |
| **Ship vulnerable if** $C$ **>=0.005** | | **Vulnerable** | **Safe** |

## E. *Comparison with previous numerical results*

In references [6] and [7], numerical simulations were performed of the parametric roll and surfriding of the tuna fishing vessel analyzed in this work. From the first of those references, in Fig. 16 it is shown the variation of roll angle in time, with and without damping. With no damping roll increases up to about 15 degrees, and with a damping corresponding to 1% of the critical, basically the roll is null; these results were obtained with encounter frequency equal to twice the roll natural frequency.

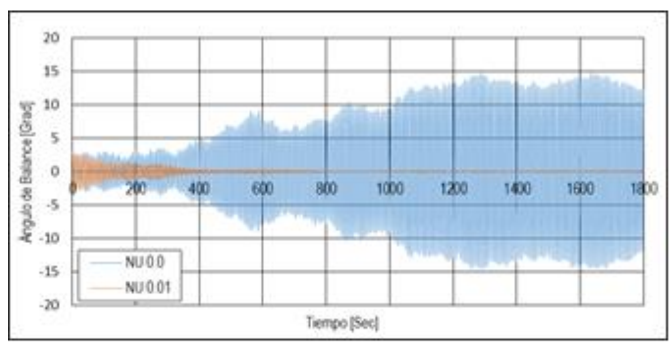


Fig. 16 Roll angle variation in parametric resonance, with and without damping, loading condition 1, [6]

In reference [7] numerical simulations were developed for the fishing vessel, with regular waves coming from stern. It was found that it is possible that regular waves capture the ship and force her to move with the wave. In figure 17, it is shown for three wave lengths corresponding to 0.75, 1.00 and 1.25 of the ship $L_{bp}$, the required wave amplitude for the ship to start surfriding. From the upper figure, for Froude numbers of around 0.295, a wave amplitude of 0.0125 times ship length (about 50 cm), the ship rides on the wave train in load condition 1. In the second loading condition, there are also possibilities that the ship may be captured by waves, but these combinations are reduced compared with the first condition.

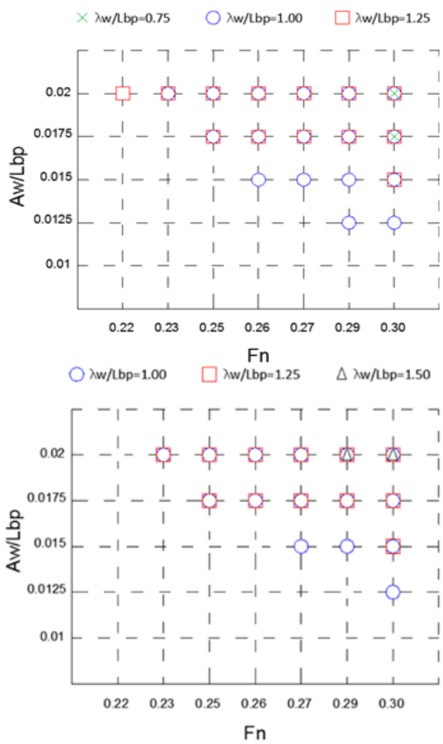


Fig. 17 Combinations of wave amplitude and length, and velocity that can produce ship surfriding, [7]

### F. *Sensitivity of results*

In [13] it was investigated the sensitivity of the previous results, considering that the main variable is the velocity of the ship. In table VIII, results for different speeds are shown for both loading conditions. It looks that a small reduction in velocity can take the ship from Vulnerable to Safe operation to ride on the waves.

TABLE VIII
SURF RIDING SUMMARY RESULT

| **Load cond.** | **Port departure** | | **Port arrival** | |
|---|---|---|---|---|
| Ship vel. [knots] | *C* | *Result* | *C* | *Result* |
| 10 | 0.00066 | **Safe** | 0.00014 | **Safe** |
| 11 | 0.00322 | **Safe** | 0.00287 | **Safe** |
| 12 | 0.0054 | **Vulnerable** | 0.00478 | **Safe** |
| 13 | 0.0077 | **Vulnerable** | 0.00692 | **Vulnerable** |

## CONCLUSIONS AND RECOMMENDATIONS

The tuna fishing vessel analyzed in this work is not expected to fail in the modes Pure loss of stability, Parametric Roll and Deadship condition, since satisfies the requirements at the first level of vulnerability of the new IMO intact stability criteria. Also according to the present results, the ship did not satisfy the requirement at the two levels of vulnerability of the Surfriding, in the first load condition so she is prone to this mode of failure; in the second load condition even though the evaluation says that there is not failure, the coefficient is very close to the limit. These findings are consistent with numerical integrations from references [6] and [7], which concluded that the ship is not expected to roll with large amplitudes in parametric resonance, but if she receives waves from the stern, they can capture the ship and obligates her to advance at the wave celerity, in one of the loading condition, being close to the failure in the second one. This is particularly dangerous, since ship surfriding may be followed by broaching and eventually to capsize. This confirms the usefulness of the stability evaluation procedure in development by IMO.

It would be useful to perform numerical integrations of the other two modes of failures, Pure loss of stability and Deadship, with this vessel. To confirm that in those modes results are also consistent with the evaluations at first level of vulnerability of this new criteria, which establish that this ship is not prone to those forms of capsizing.

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