Safety and operability of small fishing vessels: Study of a series of stability-related accidents

F. Mata-Álvarez-Santullano

A. Souto-Iglesias

ABSTRACT: The intact stability of five small Spanish fishing vessels with ages between 3 and 8 years old which sunk in stability related accidents between 2004 and 2007 is compared to the stability of the fishing vessels which were retired from service to build those. The seakeeping performance of both sets of vessels is also compared. The differences found between the results obtained by the two methods have been analyzed. The suitability of seakeeping methods to assess stability performance is discussed.

1 INTRODUCTION

Between November 2004 and September 2007, five Spanish-flagged fishing vessels capsized due to loss of stability resulting in a large part of their crew dead. From the 46 crew members on board of the five vessels 32 died or were declared missing. Examining the five accidents side by side, it is noticeable that the vessels had similar characteristics, in particular that they had all been built between 1999 and 2001 and their lengths ranged between 15 and 24 meters. When they capsized, their age ranged from three to eight years.

The vessels had been designed and built according to the Spanish stability regulation, which included the International Maritime Organization (IMO) stability criteria for fishing vessels (BOE, 1970), basically unmodified since 1970. However, the construction projects for these vessels had been elaborated not only adjusting to this framework but also complying with the Royal Decree (RD) 2287/1998, approved shortly before these vessels were designed and built. This legislation substantially changed the existing regime in Spain regarding the fishing vessels tonnage limitation and, hence, introduced new factors in their design that did not previously exist.

The shipowners, masters and crews of the capsized vessels were the same ones that had been operating the vessels decommissioned to build the new ones. Moreover, the uses of the capsized vessels were not very different from the old ones since they operated in the same area, using the same fishing gear type and in the same social framework. The old vessels were operated many years without stability problems reported. It is of interest, therefore, to compare the stability between the lost vessels and the vessels that were decommissioned to build those, which will be referred to as "predecessors".

In addition, the idea that the relationship between safety and operability needs to be studied arises. The masters operate the ships responding to the fulfillment of operability criteria and interrupt fishing operations only when those are surpassed and operation is not possible. They are hence the first to assume that a ship with a larger operability range is a safer ship. This relation needs a rigorous assessment which the authors aim at conducting in this paper by analyzing the aforementioned reference case studies.

The analysis of links between safety and seakeeping has been explored by some authors under several approaches. Tello et al. (Tello, 2011) have proposed a methodology based on seakeeping calculations for the analysis of fishing vessels operability. They studied several vessels of the Portuguese fishing fleet, proposing operability criteria with their corresponding limiting values. They concluded that roll and pitch criteria are the most often exceeded ones, and identified some trends for hull shape to optimize the fulfillment of those criteria.

The paper is organized as follows: First, the statistical anomaly that the case studies suggest is established. Then, design parameters and characteristics of the lost vessels are compared with those of the vessels decommissioned to build those. The relationship between those parameters and the tonnage of the vessels is made clear, shedding light on their dependence to the fishing effort control regulations. Second, results for intact stability and operability based on seakeeping analysis are presented and compared between the families of new vessels and decommissioned ones. Finally a discussion is provided concerning 1) negative effects of the tonnage over ship stability of the 2) the limitations of the IMO transversal stability criteria with respect to prevention of stability failure and the suitability of operability based criteria to help in fishing vessels safety assessment.

2 CHARACTERISTICS OF THE SPANISH FISHING FLEET

2.1 *Fishing vessels replacement scheme in Spain*

The control of fishing effort is a vital part of fisheries management. In the framework of the European Common Fisheries Policies (CFP), tonnage and propulsion power limitation have been tools to exert such control. Promulgations of the Multi-Annual Guidance Programmes in the period 1983–2007 (Pérez-Labajos, 2012) were major milestones in these policies. In order to fulfill the objectives of the 1997 program (EC, 1998) as well as promoting the modernization of the fleet, a specific regulation, the Royal Decree (RD) 2287/1998, was approved in Spain in 1998.

Table 1. GT increase factors from RD 2287/1998.

Regime A	Factor
Territorial and European waters	
Trawlers	1.7
Fixed fishing gears	1.6
Seiners	1.35
Regime B	Factor
International and third country waters	
Trawlers	1.7
Fixed fishing gears	1.6
Seiners	1.4

Following the approval, two different regimes to set tonnage of new fishing vessels were established, depending on the ship length:

A. Ships with a length smaller than 15 meters: the GT of the new ship could be increased by a factor of 1.1 on the total GT of the decommissioned ship.
B. Ships with a length larger than or equal to 15 meters: the GT of new ships could be increased on the total GT of the decommissioned ship by a factor according to Table 1.

For ships with an overall length larger than or equal to 15 meters, the volume below the main deck of the new vessel could be increased by 10% with respect to that of the de-registrations. Therefore, the increase contemplated in Table 1 should be achieved in practicality by closed spaces above the main deck.

2.2 *Size of the fleet*

The Spanish Ministry for Agriculture, Food and Environment (MAGRAMA) keeps the Spanish Fishing Fleet Register (SFFR) of Spanish fishing vessels in which relevant data, such as length, tonnage, power, year of registration, cause of the de-registration, de-registration year, fishery, etc. are stored. This census is accessible online on the ministry's web page (http://www.magrama.gob.es/es/pesca/temas/la-pesca-en-espana/censo-de-la-flota-pesquera/censo.asp). The European Union maintains a general fishing vessel database for all EU countries, accessible through the link (http://ec.europa.eu/fisheries/fleet/index.cfm?lg=en). Finally, the Spanish Maritime Accident and Incident Investigation Standing Commission (CIAIM) is the competent body in the investigation of maritime accidents in Spain. CIAIM publishes accident reports as well as annual reports with accident statistics on its site (http://www.ciaim.es). Using the data collected from these sources it is possible to carry out a statistical analysis of the Spanish fishing fleet.

A total of 26780 fishing vessels have been commissioned in Spain since 1870. Their distribution

Table 2. Spanish fishing vessels built since 1870.

Overall length	L > 24	24 ≥ L > 15	15 ≥ L > 6	L ≤ 6	Total
Dredges	0	0	87	201	288
Gillnet/entangling	48	351	7446	7987	15832
Hook and lines	466	378	1775	1371	3990
Traps	1	8	113	115	237
Trawls	1751	1894	692	38	4375
Total	2641	3505	10897	9737	26780

according to length and fishing gear is presented in Table 2.

2.3 *Loss rate in the Spanish fishing fleet*

From the available data in SFFR and maritime accident data collected by CIAIM it is possible to establish some statistics about the loss rate in the Spanish fishing fleet that can be applied in our study.

Using MAGRAMA data, an empirical cumulative distribution function of lost fishing vessels for flooding (including vessels lost for stability failure) as a function of the vessel age can be obtained. From this distribution the sinking probability of a vessel under 9 years old can be estimated as 0.102.

In addition, the available CIAIM data allows us to estimate at 4 per year the expected number of lost fishing vessels in Spain due to flooding.

3 LOST FISHING VESSELS CASE STUDIES

3.1 *General*

As advanced in the introduction, between November 2004 and September 2007 five Spanish-flagged ships capsized due to transversal stability related causes.

These vessels are named in this paper as F1 to F5 (Table 3). The five vessels are presented in Figures 1 to 5.

In order to comply with the CFR regulations in force, to build one new fishing vessel, one or more existing fishing vessels accounting for the same tonnage had to be decommissioned. For comparative purposes, the five fishing vessels retired from service to build F1 to F5 are referred to as "predecessors", and named as P1 to P5.

The case studies (F1 to F5) lengths are in the segment between 15 and 24 m and belong to the Seines, Liners, and Gillnets and entangling nets gear vessels categories. According to these characteristics, the vessels belong to a subgroup that comprises only 6% of the Spanish fishing vessels.

3.2 *Probabilistic assessment of the occurrence of the accidents*

As discussed previously, the sinking probability of a vessel under 9 years old can be estimated as 0.102 and the expected number of lost flooded fishing vessels per year can be estimated as 4. We therefore expect 12 losses in 3 years, which is the period that includes the case studies. Assuming each accident as an independent random event, the number of losses under 9 years follows a binomial pattern and the probability of having 5 or more of these vessels out of the expected 12 is around 0.005.

Also, as aforementioned, the case studies belong to a group of vessels that includes only 6% of the total amount of Spanish fishing vessels. Using a similar reasoning we can infer that having 5 or more of those vessels out of 12 lost in 3 years is 0.0005. To conclude, the probability that both conditions hold simultaneously is negligible, which indicates that the losses may not be independent and that therefore deserve a specific investigation.

3.3 *Main characteristics comparison*

Main dimensions and other characteristics of the studied vessels are presented in Table 4, where:

- Loa: length overall.
- V1/V2: ratio between volume over main deck included in tonnage calculations (V1) to the volume below main deck included in tonnage calculations (V2).
- GT: gross tonnage.
- Fb/B: ratio between freeboard (Fb) to breadth (B).
- GM: transverse metacentric height.

The ships in this table are referred to using their code in the European fishing vessels database (http://ec.europa.eu/fisheries/fleet/index.cfm?lg= en).

Table 3. Lost vessels case studies.

Vessel	Gear type	Year of build	Year of loss	Cause of accident
F1	Seines	2001	2004	Lack of stability; probably surf-riding and broaching
F2	Hook and lines	1999	2004	Lack of stability, probably overloading
F3	Seines	1999	2004	Lack of stability, probably surf-riding and broaching
F4	Gillnets and entangling nets	1999	2006	Lack of stability, probably dead ship condition and fishing spaces flooded
F5	Seines	1999	2007	Lack of stability, probably inadequate weight distribution

Figure 1. Vessel F1.

Figure 2. Vessel F2.

Figure 3. Vessel F3.

Figure 4. Vessel F4.

Figure 5. Vessel F5.

4 STABILITY CALCULATIONS

The vessels stability is checked against some of the IMO stability criteria for fishing vessels proposed in the the «Code on intact stability for all types of ships covered by IMO instruments », approved by the IMO Assembly Resolution A.749(18). These criteria are presented in Table 5.

Intact stability calculations have been performed by means of state of the art naval architecture software. For each lost fishing vessel and her respective predecessor, a characteristic loading condition is established. Each vessel has been studied in one loading condition only, chosen from the available information, normally being the full load condition. In the case of vessels for which no stability booklets were available (most predecessors) using the best available information a loading condition close to the full load is estimated. For the cases where the stability booklet is available small differences have been found between the calculated cross-curves and the ones in the booklet, mainly attributed to the hull modeling process to introduce hull form data into the naval architecture software.

Stability GZ curves for the ten vessels studied have been obtained and compared. In the five cases the lost vessel had lower GZ values than her corresponding predecessor in a heel angle range between 0º and 45º. Comparing the maximum GZ

Table 4. Lost vessels case studies compared with their predecessors.

Vessels/code	Gear type	Loa (m)	V1/V2	GT	Fb/B	GM (m)
F1—ESP25057	Seines	17.0	0.65	34.2	0.05	0.41
P1—ESP16060	Seines	15.0	0.31	17.1	0.12	0.84
Ratio F1/P1	–	1.1	2.1	2.0	0.4	0.5
F2—ESP24593	Hook and lines	16.0	1.12	30.0	0.14	0.68
P2—ESP05174	Hook and lines	11.3	0.64	5.9	0.09	0.93
Ratio F2/P2		1.4	1.8	5.1	1.6	1.4
F3—ESP24391	Seines	18.0	0.49	44.8	0.07	0.76
P3—ESP05969	Seines	14.1	0.31	28.7	0.09	1.38
Ratio F3/P3		1.3	1.6	1.6	0.8	0.6
F4—ESP24358	Gilnets and entangling nets	20.5	1.49	87.0	0.06	0.62
P4—ESP00251	Gilnets and entangling nets	16.0	0.52	47.0	0.13	1.10
Ratio F4/P4		1.3	2.9	1.9	0.4	0.6
F5—ESP24199	Seines	19.4	0.50	59.0	0.13	0.96
P5—ESP05154	Seines	15.8	0.28	29.0	0.09	1.20
Ratio F5/P5		1.2	1.8	2.0	1.5	0.8

Table 5. Intact stability criteria.

Criterion	Magnitude to check	Criterion type	Limiting value
C1	Area under GZ curve between 0° and 30°	Not less than	0.055 rad · m
C2	Area under GZ curve between 0° and 40° or flooding angle	Not less than	0.090 rad · m
C3	Area under GZ curve between 30° and 40° or flooding angle	Not less than	0.030 rad · m
C4	GZ at a heeling angle of 30° or more	Not less than	200 mm
C5	Heel angle corresponding to maximum GZ	Not less than	25°
C6	Initial metacentric height (GM)	Not less than	350 mm

Table 6. Stability Index (SI) of the lost vessels (F1 to F5) and their predecessors (P1 to P5).

Lost vessel	SI_F	Predecessor	SI_P	Ratio SI_P/SI_F
F1	2.7%	P1	11.0%	4.6
F2	9.9%	P2	19.7%	2.0
F3	6.7%	P3	51.0%	7.6
F4	10.1%	P4	8.0%	0.8
F5	2.0%	P5	37.0%	18.5

in that heel angle range between each lost vessel and predecessor, the ratio in the five cases ranges from 1.2 to 1.9.

To compare the regulatory stability between two vessels an index related to the KG margin is used. For each vessel the higher KG (centre of gravity height) for which all the stability criteria in Table 5 are fulfilled is computed; this is the Limiting KG. Then, the Stability Index (SI) for comparison for each vessel is the ratio between the Limiting KG and the actual KG of the loading condition studied. This SI is presented in percentual terms, and gives an idea of the reserve of stability of the vessel. Results are presented in Table 6.

5 OPERABILITY CALCULATIONS

The seakeeping performance of the ten vessels has been analyzed. A short-term seakeeping analysis has been carried out checking ship motions against a series of criterion limiting the ship operability. Tello (Tello et al., 2011) has proposed operability criteria for fishing vessels. For the purposes of the investigation only the criteria related to vessel motions have been considered among the ones proposed by Tello. For the operability analysis presented in this paper the criteria used are listed in Table 7.

Motions response operators have been calculated using the PRECAL linear seakeeping code. PRECAL computes ship motions in frequency domain using a 3D panel boundary element method formulation (PRECAL 2010, Chow & McTaggart 1996).

Table 7. Operability criteria.

Criterion	Prescribed value
Vertical acceleration (at bridge, working deck fore and working deck aft)	0.2 g (rms)
Lateral acceleration (at the previous three points)	0.1 g (rms)
Roll	6° (rms)
Pitch	3° (rms)

A nonlinear roll damping coefficient of 0.12 has been considered for roll motion, similar to the value chosen by Tello, considering that same types of vessels are under analysis in our research. The x, y, z inertia radius ratios vs B, Lbp, Lbp have been estimated by the PRECAL code, and take values between 0.32 to 0.38 for roll, 0.25 for pitch, and between 0.27 and 0.29 for yaw. These values are similar to the ones used by Tello et al., (2011), 0.4, 0.25 and 0.25 respectively.

Vertical and lateral accelerations have been computed in three points in each vessel (working deck fore and aft and the bridge), choosing the largest value for checking the criterion fulfillment. Calculations have been performed for headings 0° to 180° (head seas) in steps of 30° and vessel speed from 0 to 10 knots in steps of 2 knots.

The operability study has been performed in two sea conditions defined by the significant wave height and modal wave period according to the standardized scale adopted by NATO (STANAG 4194, 1983). For all vessels SSN4 and SSN5 have been studied, corresponding to significant wave heights of 1.88 m and 3.25 m with modal periods of 8.8 s and 9.7 s respectively.

5.1 *Operability index*

For comparative purposes an Operability Index (OI) has been defined, calculated as the percentage of combinations speed-heading at which the vessel operates complying with all operability criteria. The OI can be rigorously established using an auxiliary function Z which depends on speed and heading and. Defining Z as a Boolean function which takes the value 1 when at least one criterion is surpassed and 0 for the safe zone, it is possible to define an operability index, see equation 1:

$$OI = 1 - \int_0^{\pi}\int_0^{10} \frac{z(\theta,v)dv \cdot d\theta}{10\pi} \tag{1}$$

Operability indexes have been obtained for the ten studied ships. The loading conditions studied are the same as in the stability study.

Table 8. Operability indexes of the lost vessels (F1 to F5) and their predecessors (P1 to P5).

OI SSN4	F1-P1	F2-P2	F3-P3	F4-P4	F5-P5
Lost vessels	0.94	0.81	0.86	0.92	0.91
Predecessors	0.47	0.00	0.90	0.52	0.83
Ratio OI_P/OI_F	0.50	0.00	1.05	0.57	0.91
OI SSN5	**F1-P1**	**F2-P2**	**F3-P3**	**F4-P4**	**F5-P5**
Lost vessels	0.17	0.15	0.30	0.62	0.59
Predecessors	0.08	0.00	0.31	0.08	0.32
Ratio OI_P/OI_F	0.47	0.00	1.03	0.13	0.54

Table 8 summarizes the calculated operability index for all vessels, for the operability criteria considered.

6 ANALYSIS

Analyzing Table 4, in all the case studies, a relative increase of the ratio between the volume above and below the tonnage deck can be seen. This is reflected in the value of the ratio of V1/V2 being substantially larger for the lost vessels than for their predecessors. These volume distributions, chosen by the ship designers, are consistent with the possibilities offered by the 1998 fishing effort control regulation. This increase of the volume above main deck implies higher weights and more lateral area exposed to the wind; both issues penalize marginal stability. Observing again Table 4, a significant reduction in the ratio between freeboard and breadth is present in four out of the five case studies (apart from fishing vessel F5, with a significant freeboard increase). This freeboard reduction, which penalizes safety margins in regards to green water events and stability curve, was expected as a response from the designers to the challenge offered by the extra weight above waterdeck due to the extra volume present there.

Regarding the stability, a significant GM reduction is present in four out of the five cases (apart from vessel 24199, with a slight reduction but remaining far above the IMO threshold).

In addition, it is remarkable that most predecessors have larger stability indexes than the newer vessels that substituted them. For the pairs F1-P1, F3-P3 and F5-P5 the differences are noticeable. It is also remarkable that vessels F1 and F5, although complying with the criteria, had very little stability margin.

Regarding the operability, some conclusions can be drawn:

1. Most of the lost vessels had greater operability that their predecessors. This difference is more

noticeable in SSN4, where significant differences are found in F1, F2 and F4 with respect to P1, P2 and P4 respectively.
2. For all vessels, operability deteriorates with increasing sea states. In SSN4 all lost vessels (F1 to F5) maintain high levels of operability, with OI between 0.81 and 0.96. Lost vessels operability deteriorates significantly in SSN5, except for F4 and F5, that still have OI of 0.62 and 0.59 respectively. Being these two vessels the largest ones amongst the ten studied, their having a larger operability is expected.
3. Regarding the predecessors, more heterogeneity is found. Apart from P2, the OI of the other four vessels varies from 0.47 to 0.90.

7 CONCLUSIONS

Evidences have been presented indicating that a series of stability loss related accidents with fatal consequences that took place between 2004 and 2007 are a statistical anomaly worth studying. This series of accidents share some common characteristics that suggest a relationship between them and the approval of the Spanish RD 2287/1998, regulating the fishing effort. Such regulation allowed, in practical terms, for the increase of enclosed spaces above the main deck in new vessels aiming at improving the health and safety and working conditions of fishermen.

It has been shown that due to this regulation, the lost vessels presented a set of ratios between their principal dimensions and stability parameters significantly different from those of the vessels built before the entry into force of the 1998 norm. All these differences point in the direction of a reduction of the ship stability margins.

As a main result, the comparison between the stability characteristics of two sets of vessels and the comparison between the operability characteristics of the same two sets of vessels throw opposite results. While the predecessors had in general more stability, the lost ones had in general larger operability. It means that the masters of the new fishing vessels could have considered them to be safer, as experienced in general lower motions and accelerations, while in fact the new vessels were less stable than their predecessors, and might require a more careful operation.

Summarizing, the facts discussed in this paper suggest that the 1998 fishing effort control related tonnage limitations may have had a negative effect over the stability of some kinds of fishing vessels with dramatic consequences. Regulators and policy-makers should bear in mind that safety is a transversal aspect to all regulations affecting ship design, and that a strong maritime safety assessment should be performed during the approval process of any maritime regulation.

Overall, these results indicate that usual operability criteria may not contribute much to assess ship safety during design phases. It also suggests that masters should be strongly trained in stability, so they are able to manage adequately their vessel stability regardless the operability behavior.

As a final remark, taking again into account that the sunk vessels fulfilled IMO stability criteria and had larger operability than the predecessors, we believe that more effort is needed to develop and validate new, more complex stability criteria, that can capture the reality of the dynamics of fishing vessels in a seaway.

REFERENCES

BOE. 1970. *Orden de 29 de julio de 1970 sobre normas de estabilidad de buques pesqueros.* Boletín Oficial del Estado nº198, 19th August 1970.

Chow, D.L. & McTaggart, K.A. 1996. *Validation of SHIPMO7 and PRECAL with a Warship Model, Technical memo.* Defence Research Establishment Atlantic Dartmouth (Nova Scotia, Canada).

EC (European Commission). 1998. *Decision of 16 December 1997 approving the multiannual guidance programme for the fishing fleet of Spain for the period from 1 January 1997 to 31 December 2001.* Official Journal of the European Communities L 39/59.

Perez-Labajos, C.A. 2012. Analysis of inequalities between the fishing capacities of the fleets of the European Union. *Marine Policy 36(2012), 630–635.*

PRECAL. 2010, *Version 6.6 User Manual.* Corporate Research Ships, MARIN.

STANAG Nº 4194. 1983. *Standarized wave and wind environments and shipboard reporting of sea conditions.* 6 April 1983. Military Agency for Standardization (MAS). NATO 7983.

Tello, M. & Ribeiro e Silva, S. & GuedesSoares, C. 2011. Seakeeping performance of fishing vessels in irregular waves. *Ocean Engineering 38(2011), 763–777.*