SOME EXPERIMENTAL RESULTS ON THE STABILITY OF FISHING VESSELS

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Model Basin. Escuela Técnica Superior de Ingenieros Navales. U.P.M. (Spain)

Abstract

Three representative models of Spanish fishing vessels have been tested in the Model Basin of the Escuela Técnica Superior de Ingenieros Navales (Universidad Politécnica de Madrid), covering several aspects of the intact stability in waves. This selection covers, in size and in type, quite well the Spanish fishing fleet. The righting arms in several regular waves have been obtained and compared with numerical values. The effects of the free-surface in the tanks have also been studied. Finally, the parametric resonance with following seas has been considered.

1. INTRODUCTION.

Undoubtedly, the intact stability is one of the most important aspect for the safety of ships and this importance is increased in small ships as the fishing vessels. Many studies point out the dangerous situations of the fishermen and their vessels[1-3].

Although some authors consider that model testing is not a perfect substitute for real ship behaviour [4], experimental research is one of the tools used in the development of performance based stability criteria [5]. Also, in [6] model tests are considered as one of the most important methods in ship stability study.

As it is stated in [7] the small commercial fishing vessels, generally less than 50 metres, are the most diverse and largest class of marine vessels in existence. Even in this case, small fishing vessels, you can find important differences between several fleet. No attempts of comparison have been found except in the work by Umeda and Renilson [8] comparing Australian and Japanese fishing vessels in directional stability and the studies presented in [9] where the hull forms of Asian fishing vessels and European ones are compared under the stability point of view.

The European vessels under the regulations utilizing ship length are much wider and deeper than Asian ones under the regulation utilizing gross tonnage. Currently displacement of a European vessel is often about twice as large as that of an Asian one for a given length. Naturally, the answer of these ships is different regarding the stability behaviour.

In this context, experimental results from three models of the Spanish fishing vessels are presented, covering several aspects of the intact stability in waves.

2. SUBJECT SHIPS.

The most recent figures of the Spanish fishing vessels fleet are: 18.023 ships with 413.093 RGT, 1.435.353 kw and 67.729 fishermen, representing one of the most important fishing fleet in the world and the first in the European Union, with annually captures of more than one million tonnes.

The selected vessels have been: Ship A, a polyvalent seiner with one deck and 21.50 metres length; Ship B, a purse seiner ("bonitero") with a length of 16.50 m and Ship C, a trawler of two decks of 34.50 metres length. The main characteristics of these ships are presented in the following table:

Table 1

Ship	**A**	**B**	**C**
L_{oa} (m)	21.50	16.50	34.50
L_{bp} (m)	17.80	13.37	29.00
B (m)	6.00	4.70	8.00
D (m)	3.00	2.20	3.65
d_{design} (m)	2.40	1.67	3.607
RGT	64	31.97	179.12
$Desp_{máx.}$ (t)	175.621	66.574	541.388

The general arrangements and the body plans of these ships are included in the following figures

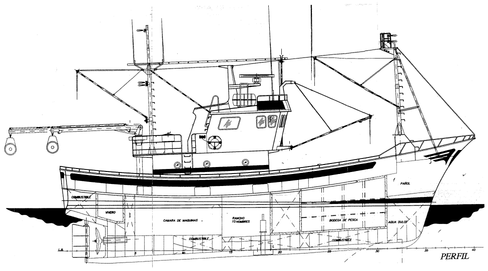

Figure 1. General arrangement. Ship A

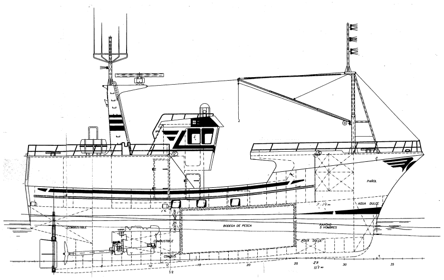

Figure 2. General arrangement. Ship B

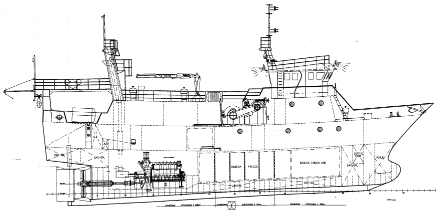

Figure 3. General arrangement. Ship C

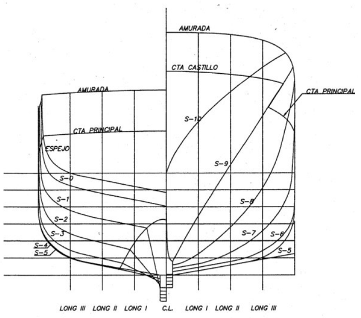

Figure 4. Body plan. Ship A

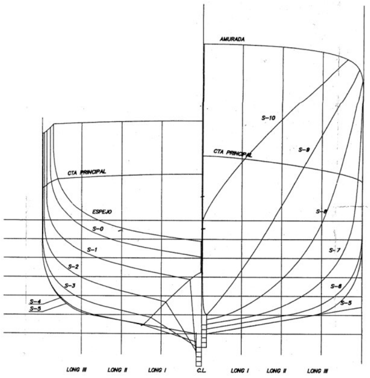

Figure 5. Body plan. Ship B

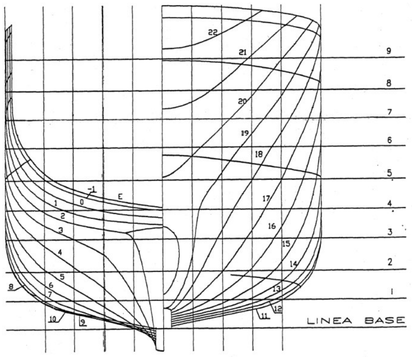

Figure 6. Body plan. Ship C

The size of these ships covert 42% of the fleet and their type represent 74% of the total fleet what means that these ships are quite representative of the Spanish fishing vessels fleet.

3. LOSS OF TRANSVERSE STABILITY ON A WAVE CREST

The loss transverse stability on a wave crest is one of the four capsizing modes of a ship model complying with the IS code, defined by Umeda & Hamamoto with capsizing model experiments [10]. This is produced by the reduction of the metacentrical height when the ship is sailing in such conditions, because the hydrostatic restoring moment is quite lower than the one obtained in still water.

This is most severe when in the case of pure following seas [11], with heading angle of zero degrees, when a ship could capsize simply due to loss of static balance by such a reduction of transverse stability. This phenomenon is known as pure loss of stability

It is widely accepted that the restoring arm decreases when the ship centre is situated on a crest of longitudinal waves, and this can be proved both mathematically and experimentally [10] and [11], and this effect is most critical when wave length value is near ship length. It is also believed that this phenomenon can be mathematically explained by integrating the wave pressure up to the wave surface with the Froude-Krylov assumption.

To confirm these actions, model experiments were carried out in the Towing Tank facilities of the Escuela Técnica Superior de Ingenieros Navales (Universidad Politécnica de Madrid) for the subject vessels. The main dimensions of the tank are 100 m length, 3.8m wide and a depth of 2.2.m. The carriage can reach a speed of 3.5m/s and a flap type wave generator positioned at one extreme of the tank generates regular waves up to a height of 0.25m and a period of 2 s.

The models scale λ was chosen considering: the tank dimensions, the stock propeller to be used in the selfpropulsion models and the range of the wavemaker. The scale models are indicated in the following table,

Table 2

Model	**A**	**B**	**C**
L_{bp} (m)	1.62	1.67	1.55
λ	11	8	18.75

The characteristics of the different loading conditions tested are presented in the table 3, corresponding to the minimum displacement situations.

Generated waves were chosen with equal length to ship length, and models were towed at wave celerity. So, wave position in respect to ship was maintained, and different positions of wave crest in respect to amidships were tested and the restoring moments for different heel angles were measured, obtaining the GZ curves . Tests were carried out this way: a known heeling moment was applied with a weight, and the heel angle produced when the ship was sailing in the different waves was measured with an inclinometer. Results of the GZ curves in waves, extrapolated to ship scale are shown in figures 7-9.

Table 3

Ship	**A**	**B**	**C**
L_{bp} (m)	17,80	13,37	29,00
B (m)	6,00	4,70	8,00
D (m)	3,00	2,20	3,65
d_{design} (m)	1.947	1.391	3.292
KG(m)	2.308	1.930	3.921
GM(m)	0.934	0.715	0.350
GM_c(m)	0.927	0.695	0.350
T_ϕ(s)	4.64	4.47	10.83
Rad.$_{long}$(m)	4.93	4.41	8.41
Rad.$_{trans}$(m)	2.24	1.785	3.204
Disp.. (t)	122.9	49.0	470.9

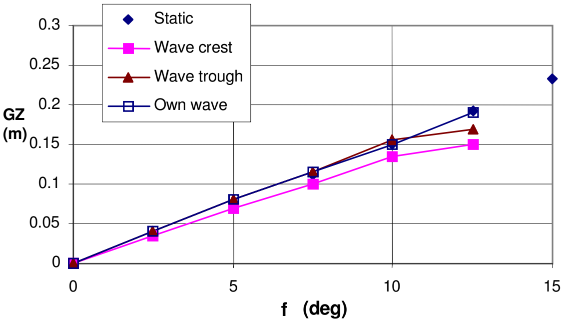

Figure 7. Righting arms. Ship A

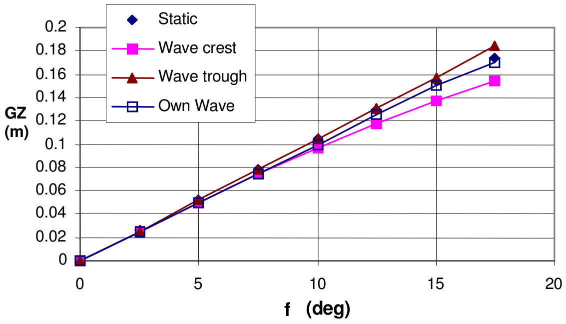

Figure 8. Righting arms. Ship B

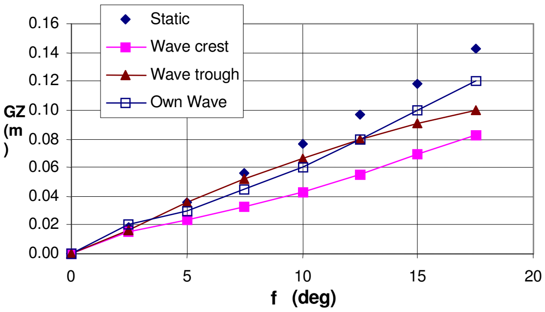

Figure 9 Right arms. Ship C

From these figures can be seen the loss of stability when the wave crest is placed amidships. Even when the ship is sailing without waves, only in its own radiated wave, there is a small loss of stability. To get a global value of the loss of intact stability, if the initial GM value is calculated for the ship in waves, a reduction of the GM value of 13%, 19% and 11% for ships A, B and C respectively is obtained in respect to the static value of the GM, that is a well known criteria of the intact stability.

Numerical modeling is an important part in the study of sea-keeping problems, particularly as a problem is non-linear. However, any numerical model should be verified by model- or full-scale measurement before being applied for analysis of a practical problem, since there are always some assumptions made under the derivation.

Normally, validation of theoretical calculation should at first hand be made for regular waves for a wave-induce problem, even though this kind of wave rarely appears in reality. The reason is that this kind of wave is well defined mathematically. However, it is not a simple task to generate a perfect regular wave with desired parameters in a wave basin. The generated waves are always disturbed in some degrees. Therefore it is important to make proper treatment of the measured data before being used for the purposed validation.

As mentioned, the Froude-Krylov assumption can be used to obtain the effect of regular waves on ship stability. Nevertheless, this theory has some limitations, e.g. it is assumed slender ships and high frequency of oscillation [12]. Fishing vessels have low Lbp/B ratios and are not an example of slender ships. In the case of pure loss of stability in following seas, encounter frequency is low. So, the mentioned assumption shows limitations to model the problem.

According to [13], in the case of following seas where the ship is sailing at wave speed, the viscous effects of the speed can be neglected in respect to the hydrostatic forces that appears due to the variation of the waterplane form due to the effect of the wave. If the wave profile (Fig. 10) is used to obtain the GZ curve, with the wave crests in a fixed position with respect to amidships, the pure loss of stability can be seen. For every heel angle, the equilibrium condition and GZ value is obtained.

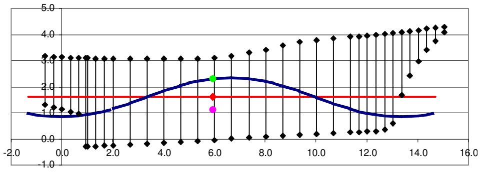

Figure 10. Wave profile to obtain GZ curve

Calculations were validated for the three models at different wave crest positions with respect to amidships and for different loading conditions. Some validation results of the GZ curve of ship A with the wave crest amidships can be seen in Fig. 11. (0.5 in the legend)

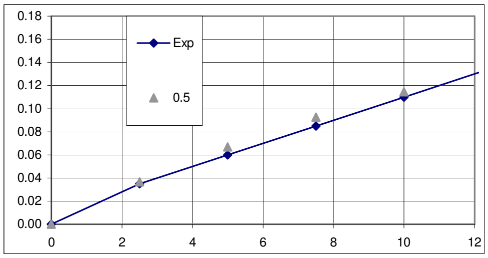

Figure 11.

For the validation results of the different cases, the method using the wave profile to obtain the GZ curves show a good agreement, at least at low heel angles (<20º) that is the range used in the tests. For greater heel angles, were the deck is submerged and there will be interaction and dynamical effects between the wave, water on deck and superstructure, the method is supposed to be less accurate than for low angles.

4. THE EFFECTS OF FREE SURFACES OF LIQUIDS IN TANKS.

It is well known that an unpleasant surprise that can ruin stability may result from internal liquids of any sort. Under a static point of view, the motion of the liquid in a tank that is partially full reduces a ship's stability because, as the ship is inclined, the center of gravity of the liquid shifts towards the low side. This causes the ship's center of gravity to move towards the low side, reducing the righting arm.

The usual practice in evaluating the effect of free surface in a ship's tank is to assume the most unfavourable disposition of liquids likely to occur. It is customary to assume that the largest tank in each of the systems, is half full. The theoretical effect of free surface is assessed by assuming that the free surface angle is the same as the roll angle and with the same phase angle.

Dynamic effects, that are not considered, can modify the aforementioned results. Experimental data [14] and numerical calculations 15] show that the free surface behaviour in tanks manifest strong features of non-linearity. In some situations, these effects can be more dangerous than in the worst static assumption as is presented in [16]

If we look this action in the International safety regulations we find that the effect of free surfaces of liquids in tanks in the intact stability is considered in the paragraph 3.3 of the IMO IS Code saying that the initial metacentric height and the stability curves should be corrected for these effects.

This correction is purely static and the values of the free surface moment given by the expression of the paragraph 3.3.3 corresponds to a parallepipedic tank in the 50% full condition without any restriction to the breadth.

The paragraph 2.3.5 of the mentioned Code indicates that the number of partially filled or slack tanks should be kept to a minimum because of their adverse effect on stability as a general precaution against capsizing. An special consideration of the anti-rolling devices is stated in the paragraph 3.1.2.7. Nevertheless, any restriction is imposed to the tank breadth.

Although it is a very good shipbuilding practice to reduce the breadth of the tanks in order to reduce the dangerous presence of free surfaces, the SOLAS, under the point of view of the safety of life at sea, does not consider any prescription about the tank breadth. The MARPOL prescriptions consider longitudinal subdivision in order that the cargo tanks verify the capacity requirements but there is not any reference to the tank width due to intact stability problems.

In order to analyse the influence of the tank breath in the free surface actions in the rolling motion the three subject models were tested with beam seas. These tests were carried out without free surfaces and with different tank configurations, including free surface effects.

The ships A and B were tested in the condition of minimum displacement. As in the Ship C, the GM was 0.35 m and no correction by free surfaces was allowed, a new loading condition was selected, named C_STANDARD, which characteristics are included in Table 4.

Table 4.

Ship	**C_Standard**
L_{bp} (m)	29.00
B (m)	8.00
D (m)	3.65
d_{design} (m)	3.4442
KG(m)	3.489
GM(m)	0.776
GM_c(m)	0.776
T_{ϕ}(s)	6.93
Rad.$_{long}$(m)	8.41
Rad.$_{trans}$(m)	3.052
Disp.. (t)	505.4

In each model, the following tank configurations were considered:

- Without free surfaces
- With two tanks, half ship breadth each one
- With one tank, all ship breadth

The tanks were constructed in methacrylate and changes were done in order to keep the displacement, drafts, inertias, center of gravity position, etc. of the loading conditions selected. In the cases “without free surfaces”, the space between the water and the tank was filled up with expanded polystyrene, keeping all the values without any actions from the free surfaces. The characteristics of these tanks are presented in the two following tables for the one and two tanks configurations respectively.

Table 5. One tank

Ship	A	B	C
L_t (m)	1.43	1.04	2.00
B_t (m)	5.50	4.00	6.64
D_t (m)	1.10	0.80	1.95
h_{water} (m)	0.55	0.40	0.84
$Vol_t(m^3)$	4.3	1.664	1.664
Situation	stern u/deck	center u/deck	center u/deck

Table 6. Two tanks

Ship	A	B	C
L_t (m)	1.43	1.04	10.95
B_t (m)	2.75	2.00	3.24
D_t (m)	1.10	0.80	1.95
h_{water} (m)	0.55	0.40	0.84
$Vol_t(m^3)$	2.16	8.832	30
Situation	stern u/deck	center u/deck	center u/deck

Model tests with beam regular waves were conducted in the towing tank. The model was situated perpendicular to the tank length. The wave height was measured by a resistive type gauge and the rolling motion by a inclinometer inside the model. The wave slope was 3 degrees. The figures 12-14 present the amplification factor (rolling amplitude divided by wave slope angle) versus period in the three configurations: without tanks, with one tank and with two tanks.

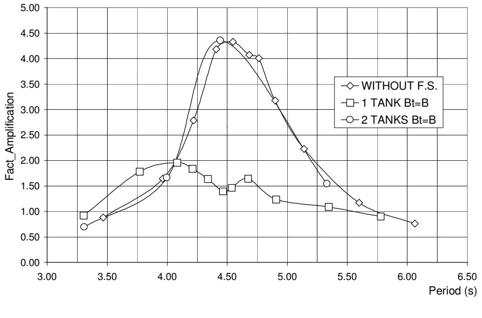

Figure 12. Ship A

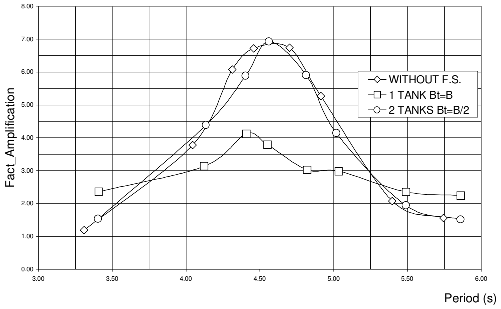

Figure 13. Ship B

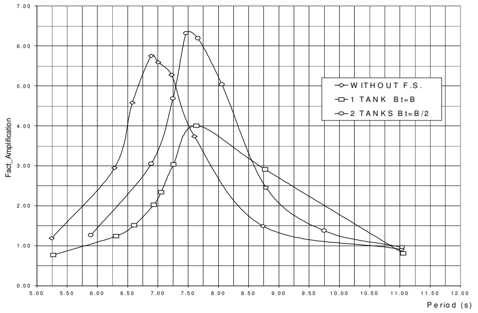

Figure 14.- Ship C

The action of the tanks with a breadth around half of the ship's breadth is to increase slightly the resonant period of the ship. In these cases, the natural period of the tanks is smaller than the ship natural period. The free surface of the tank is horizontal with respect an observer outside the ship. As the natural period of the tank is proportional to the tank breadth, it can be concluded that with tanks which breadth is equal or less than the half of the ship's breadth, the behaviour of these tanks is equivalent to the quasi-static case and no dangerous non-linear consequences in the rolling motion appears.

In the case of the tanks of similar breadth to the ship breadth, in the resonant frequency, the amplitudes of the roll motion are damped, but for greater and smaller frequencies, the roll amplitudes can be amplified as it was also mentioned by Amagai et al.[17] . In this case the free surface of the tank is not longer horizontal with respect an observer outside the ship but with a very agitated motion.

5. PARAMETRIC ROLL RESONANCE.

In following seas, if the encounter period is a multiple of half of the roll period, the roll motion develops with a period equal to the natural roll period. This is commonly known as the parametric roll resonance. The regime of parametric roll period in which the encounter period is half of the natural roll period is often called low cycle resonance or principal resonance; it is the most significant regime and may easily lead to capsize.[18]

Some capsize occurs with relatively small metacentric heights (GM) in model runs with low Froude number in following seas. Due to limitation of the IS Code, this danger occurs mainly for ships with a small GM and high freeboard. In this case the encounter period is so long that the pitch and heave motion can be regarded as static. When the heading angle increases, this danger decreases.

Experimental evidence also exists [19] of parametric roll motion in head and beam seas. In this case low cycle resonance requires a larger GM and does not easily lead to capsize.

Neves et al.[20] indicates that fishing vessels, in particular, are frequently reported to develop strong rolling motions associated with characteristic low cycle resonance. The authors' view is that for this type of vessel, with intrinsic design characteristic and operational requirements, parametric resonance is a most relevant source of dangerous situations. On the other hand, parametric resonance may be important for typical fishing vessels even in head seas.

In order to check the ability against this phenomenon, the three selected models were tested in the conditions of minimum displacement where more important variations of GM are expected. The characteristics of these situations have been already mentioned.

The data recorded in these tests were: wave height and roll motion, in a similar way as in the beam waves tests.

The natural roll period of ship A in the load condition selected is 4.64 s. In this case, the encounter period most dangerous under the parametric roll resonance point of view is 2.32 s. If we considerer the model at zero speed, the waves of this period correspond to low sea state, lower than Beaufort 2. For this reason and in order to get higher sea states it is necessary to consider head waves and the ship with the highest speed. The same consideration can be applied to the ship B.

The case of the ship C is quite different. The most dangerous encounter period is around 5.4 s. that with zero speed of the ship, corresponds to sea states of Beaufort 6. In this situation the test was carried out at zero speed (the model was fixed with an string in the transom at the flotation level) with following waves.

The conditions for these test are presented in the following table,

Table 7

Ship	**A**	**B**	**C**
V(knots)	10	9	0
T_{wave}(s)	4.16	3.93	≈5.4
H_{wave} (m)	1.00	1.00	1÷2
$T_{encounter}$ (s)	2.32	2.24	≈ 5.4

In the first two cases, ships A and B, it was not possible to get the parametric resonance phenomena. In the ship C, it was easily the get this situation, obtaining roll amplitudes of 17° for waves of 1 m. height and 28° for waves of 2m.

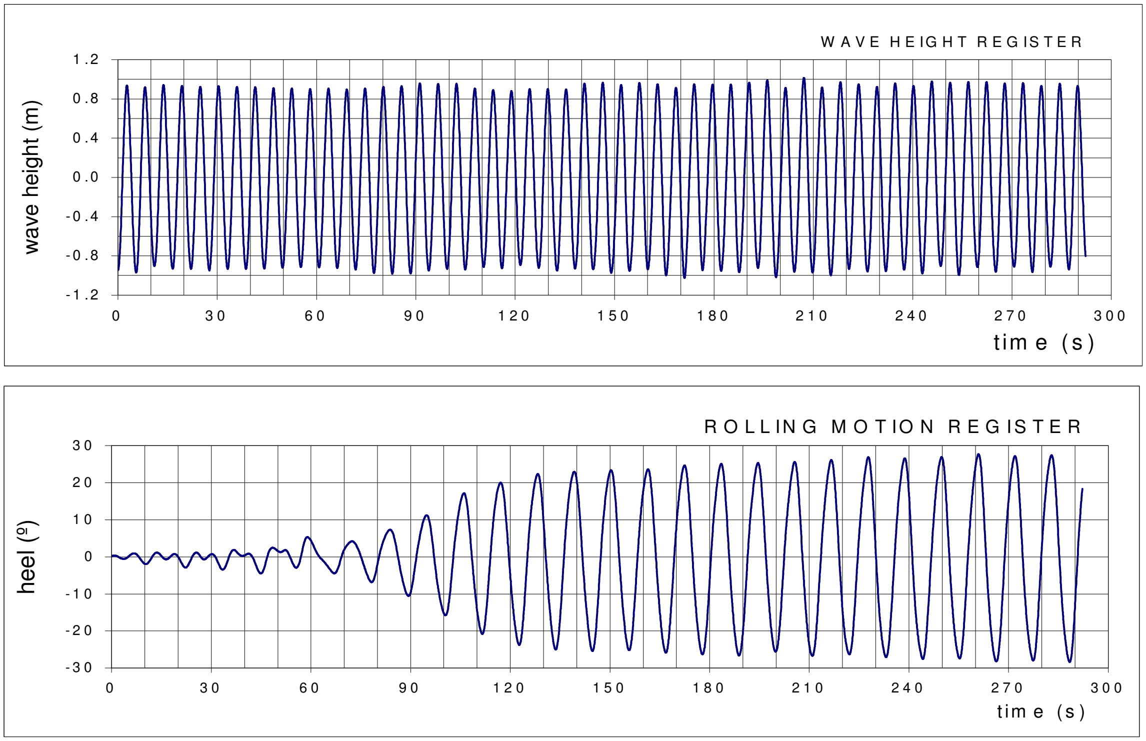

Figure 15

In the figure 15 a register of the height wave and roll motion of this phenomenon are presented. This result confirms a previous investigation [21] in which dangerous resonant parametric amplification were found for fishing vessels with a transom stern with a low metacentric height loading condition.

6. CONCLUSIONS.

Results of a series of experiments on fishing vessels stability on waves have been presented. They were undertaken for three fishing vessel models quite representative of the Spanish fishing vessels. The aspects of the loss transverse stability on a wave crest, the effects of free surfaces of liquids in tanks and the parametric rolling were investigated.

The loss of stability in waves, that is not considered in the stability requirements of the Administration, is confirmed in the three vessels and that is most severe in the case of low initial stability. Under numerical assumptions, another way to compute the loss of stability, without the Froude Krylov hypothesis is validated

The behaviour in rolling motion of tanks with breadth equal or less than the half of ship breadth, is equivalent to the quasi-static case considered in the International Safety prescriptions and no dangerous non-linear consequences in the rolling motion are expected. In the case of the tanks of similar breadth to the ship breadth, the amplitudes of the roll motion can be amplified for greater and smaller frequencies than the natural roll period of the ship.

For fishing vessels, a dangerous resonant parametric amplification can be found with a transom stern forms with low metacentric height.

Finally, all these aspects point out the necessity for the designers and shipowners of considering the dynamical effects of the waves on ships stability. The safety regulations must collect the danger that for the intact stability represent the dynamic effects of the free surfaces

7. ACKNOWLEDGEMENTS.

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8. REFERENCES.

[1] Roberts, S. E., "Hazardous Occupations in Great Britain", Lancet 2002. pp 543-44.

[2] Hall, T.A., "Stability of Capsized Fishing Vessels During Dive Rescue Operations", Marine Technology, July 1997, Vol. 34, no. 3, pp. 155-180.

[3] Pérez-Rojas, L., "La seguridad en los buque pesqueros". Ingeniería Naval, October 1982, pp. 360-379.

[4] Odabasi, A.Y., "A Note of the Conceptual Understanding of the Stability Theory of Ships". Contemporary Ideas on Ship Stability, Elsevier, 2000.

[5] Johnson, B. and Grochowalski, S., "Development of a Performance Based Fishing Vessel Stability Criteria; a Methodology Based on Scalable Model Tests". ". 6th. International Ship Stability Workshop, Webb Institute, Long Island (New York), October 2002.

[6] Belenky, V.L., "Seventh International Conference on the Stability of Ships and Ocean Vehicles (STAB'2000) - A Review". Marine Technology. Vol. 38, No 1, January 2002, pp. 1-8.

[7] Womack, J., "Small Commercial Fishing Vessel Stability Analysis. Where are we now?. Where are we going?". 6th. International Ship Stability Workshop, Webb Institute, Long Island (New York), October 2002.

[8] Umeda, N., Renilson, M.R., "Broaching in Following Seas-A Comparison of Australian and Japanese Trawlers". Bulletin National Research Institute of Fisheries Engineering, No. 14, pp. 175 – 187, 1993.

[9] Umeda, N., Iskandar, B.H., Hashimato, H., Urano, S., Matsuda; A., "Comparison of European and Asian Trawlers –Stability in Seaways-". Proceedings of Asia Pacific Workshop on marine Hydrodynamics, Kobe, pp. 79-84. 2002

[10] Umeda, N. and Hamamoto, M., "Capsize of Ship Models in Following /Quartering Waves – Physical Experiments and Non-linear Dynamics", Philosophical Transactions of the Royal Society of London, Series A, 358:1883-1904. (2000)

[11] Hashimoto, H., Umeda, N. and Matsuda, A., "Enhanced Approach for Broaching Prediction with Higher Order Terms Taken into Account". 6th. International Ship

Stability Workshop, Webb Institute, Long Island (New York), October 2002.

[12] Salvensen N., Tuck, E and Faltinsen O. "Ship motions and sea loads", SNAME Transactions, Vol. 78, 1970.

[13] Pauling J.R. "Transverse stability of ships in a longitudinal seaway", Journal of Ship Research. March 1961

[14] Van den Bosh, J. And de Zwaan, "Roll Damping by Free Surface Tanks with Partially Raised Bottom". Technical Report no. 280. Delft Technical Netherlands. 1970.

[15] Armanio, V., "An Improved Mac Method (SIMAC) for Unsteady High Reynolds Free Surface Flows". International Journal for Numerical Methods in Fluids, 24. pp. 185-214. 1997.

[16] Rakhmanin, N.N. and Zhivitsa, S.G., "The Influence of Liquid Cargo Dynamics on Ship Stability". Contemporary Ideas on Ship Stability. Elsevier, pp 377-387.. 2000.

[17] Amagai, K., Ueno, K and Kimura, N., "Characteristic of Roll Motion for Small Fishing Boats". Contemporary Ideas on Ship Stability. Elsevier, pp. 137-148. 2000.

[18] Umeda, N. and Peters, A. "Recent Research Progress on Intact Stability in following/quartering Seas". ". 6 th. International Ship Stability Workshop, Webb Institute, Long Island (New York), October 2002.

[19] Umeda, N. and Hashimoto, H., "Qualitative Aspects of Non-linear Ship Motions in Following and Quartering Seas with High Forward Velocity". Journal of Marine Science and Technology, 6, pp. 111-121. 2002.

[20] Neves, M.A.S., Pérez, N. and Lorca, O.M., "Experimental Analysis on Parametric Resonance for Two Fishing Vessels in Head Seas". 6th. International Ship Stability Workshop, Webb Institute, Long Island (New York), October 2002.

[21] Neves, M.A.S., Pérez, N. and Valerio, L. "Stability of Small Fishing Vessels in Longitudinal Waves", Ocean Engineering, Vol. 26, nº.12. 1999.