INVESTIGATION ON THE CAUSES OF FISHING VESSEL CAPSIZES BY MEANS OF MODEL TESTS. THE CEHIPAR EXPERIENCE.

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ABSTRACT

The Spanish Administration is enforced by law to investigate the causes of any serious ship accident especially if they resulted in human losses. To this purpose the Committee for Ship Accident Investigation has been created. This committee depends organically of the Spanish Maritime Authority but is completely autonomous in its decisions and way of working. Several of the most recent accidents were probably related to stability issues in waves, mostly because of stability reduction in following seas or water accumulation on deck. In these cases the CEHIPAR (El Pardo Model Basin) has been commissioned by the Committee for investigation of the circumstances of the accident by means of model tests and therefore CEHIPAR has accumulated a large experience in this kind of studies involving up to three fishing vessel accidents occurred in only two years.

This paper presents the main aspects of the methodology developed by CEHIPAR for this kind of tests and specifically:

- The gathering of information on the environmental conditions, the ship's load condition, deck arrangement, speed and course.
- The reproduction of the ship's characteristics at model scale with special emphasis on the deck arrangement: obstructions, gunwales, openings on sides and deck, and so on.
- The reproduction of the wave conditions and specially the way in which specific deterministic waves are chosen with a certain probability of having occurred in the sea state estimated at the time of the accident and that could have put the ship in danger.
- The way the tests are carried out.

In this paper we will describe the lessons learnt from the work done by CEHIPAR in the investigations related to these capsizes.

1. INTRODUCTION

In the last years the CEHIPAR (Hydrodynamic Research Center in Madrid, Spain) has closely collaborated with the Spanish Commission for the Investigation of Ship Accidents regarding the seakeeping aspects of several accidents occurring in or near Spanish shores.

Most of these accidents involved small fishing vessels sailing in relatively bad weather and it was suspected that their capsize was due to these bad sea conditions.

That this is the true cause of the accident is difficult to ascertain and this is the reason why we revert to model tests in order get a better insight into the behaviour of the ship in the sea conditions present at the time of the accident.

It is clear that unless clear evidences are available from witnesses we can only talk about levels of probability. But these studies are helpful in understanding the conditions of the ship at the time of the accident and in trying to improve the safety of similar ships.

In some cases it is interesting to also study the flooding process that leads to the sinking of the vessel. This is because the way the ship sunk (by the bow, stern, …) is a piece of information that can be available from witnesses such as rescue crews and tests trying to reproduce the sinking process can help to determine if the hypothesis about the accident are correct.

In the following we will describe the experience gained by CEHIPAR in this kind of investigations based in the testing of three fishing ships capsized recently around Spanish shores. But we have to say that part of the experience comes also from the investigation of other ship capsizes like the Prestige tanker. Also, similar studies may be found at Borlase (2002), Grochowalski (1989) and USCG (2003).

2. GATHERING OF INFORMATION

In order to model accurately the conditions in which the accidents happened, as much information as possible must be obtained about both the vessels and the environmental conditions.

The environmental conditions are considered later. Regarding the other aspects of the problem, the main sources of information for the vessel are the Administration, the shipyard, the ship owner and the declarations from the survivors (if any). From these sources, the following points must be determined or guessed:

- Ship forms and stability information: These can be obtained from the shipyard drawings, the Stability Book and Freeboard Act obtained from the Administration. It is also important to determine weather any major modifications on the vessel had been carried out such as a change of the main engine or addition of cranes and other weighty deck equipment. Sometimes these modifications are not documented and one has to revert to photographs or other sources.
- Ship loading condition at the time of the accident. This is difficult to determine, as the only reliable information comes from the statements from the survivors, that in many cases do not know the exact loading conditions due to the on board books not being up to date as most of the loading and unloading operations are routine and, of course, the sinking is unexpected. Also, the crew members at the time of the accident are under an extremely stressful situation, which leads to inaccurate statements and a lack of objective information. Sometimes is interesting to have available a twin ship which could allow, for example, to measure the rolling period in order to estimated the inertia of the ship.
- Events that may have caused the accident: The same problems stated for determining the loading conditions apply to this point. In any case, from the statements some important information may be obtained, such as any unusual noises or ship behaviour which may give a clue on the causes of the accident.
- The arrangement of the weather decks. It is important to determine the arrangements of nets and other fishing accessories on the deck. But most important is to determine the conditions of the scuppers and freeing ports as many times they are closed by the fishermen in order to obtain better working

conditions on deck. To this purpose the inspection by divers or ROV´s is very valuable if available.

- The ship speed and heading. This can be deduced from the destination and characteristics of the ship as well as from the radio communications with the owner and families. This allows us to know the heading relative to the waves if adequate wave information is available.

Once the most likely conditions are determined, tests on the basin are performed. Should capsizing not happen during these tests, further assumptions are made, based on the usual working habits of the fishermen. These will depend on the area and type of fishing performed. These may include introducing ballast on the forepeak in order to compensate the trim of the vessel when the holds are empty, stowing nets to one side of the vessel so that the launching and stowing operations are made easier. Also, undeclared nets may be carried, due to the licenses being paid based on the number and type of nets, which also depends on which fishes are being captured. The stowing of additional nets may have an important negative effect on the ship stability.

Another important point can be the study of the stability in a regular wave that can be estimated from the quasi-estatic calculation with a hydrostatics program. One example is given at Figure 1 for one of the ships. The GM in different equilibrium positions on a regular wave is give. A large reduction is observed when the ship is near the crest. This is especially dangerous in following seas when the ship can stay in the same relative position to the crest for a long time. The wave shown has a 2% of occurrence probability in two hours.

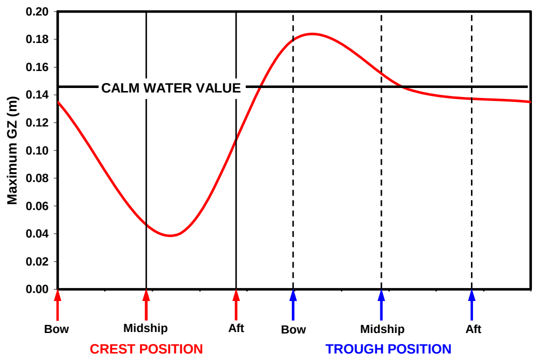

Figure 1. Instant quasi-static GM at different positions on a regular wave.

3. DESCRIPTION OF THE SHIPS AND THEIR ACCIDENTS

A total of three fishing vessels had been investigated in the last three years but, regretfully, more can be expected. The main characteristics are given in the following table.

Table I. Ship main particulars.

	Ship A	Ship B	Ship C
Length	13.5 m	15.5 m	22.5 m
Beam	5.2 m	5.75 m	7.2 m
Displacement	74 t	95 t	296 t
GM	0.580 m	1.049 m	3.122 m
Type	Purse seiner	Purse seiner	Trawler

Ships A and B have similar characteristics and they capsized in similar circumstances although the sea conditions for ship B were worse. Both were sailing in following/quartering seas. Vessel A sailed in waves of significant height about 2.7 while for vessel B the significant wave height is estimated between 3 and 3.7 meters. These conditions can not be considered extreme in normal circumstances but, as a result of the tank tests, they probably led to capsize of both ships. Both ships reported difficulties in keeping course and the tank tests confirm this problem as it was difficult to keep course with the remote controlled servo system for the rudder.

For ship C the information is sparser than for the others so that the heading could be from bow to quartering seas but most probably around beam seas. Also the weather conditions are more undefined because the nearby buoy was under maintenance and the other sources of information (hindcast data and reports from rescue vessels were inconsistent).

The estimated stability was compared with the regulations from the Spanish Administration (see Table II) and we found that one of the ships did not comply with them but by a small amount.

The three accidents happened suddenly so that, except for ship C, no radio SOS communications were given by the crew so that the accidents were detected by the automatic release of the distress buoys.

Table II. Spanish stability requirements for fishing vessels under 24 m.

Criteria	Before July 2007	After July 2007
Dynamic stab. 0 to 30º	0,055 m rad	0,055 m rad
Dynamic stab. 0 to 40º	0,090 m rad	0,090 m rad
Dynamic stab. 30ºto 40º	0,030 m rad	0,030 m rad
Minimum GZ over 30º	200 mm	200 mm
Maximum GZ	over 25º	over 30º
Initial GM	350 mm	350 mm
Hold flooding angle	N.A.	20º

4. MODEL CONSTRUCTION

In some cases the model had to be used for two completely different kinds of tests: self propelled seakeeping tests and sinking tests in calm water with simulation of water flow through the internal compartments. These two kind of tests implied very different requirements that have to be fulfilled with a single model for cost and schedule reasons.

To comply with the requirements of these two kind of tests, the model had to reproduce the typical characteristics of seakeeping models like weight, inertias, COG, etc. but it also had to reproduce as exactly as possible the internal distribution of bulkheads, communications between compartments, openings to the sea, permeabilities of each compartment and, of course, watertighness of the closed compartments. A delicate issue is the correct scaled reproductions of small openings as vents or air ducts.

To further complicate things, the seakeeping characteristics that have to be reproduced included details like the full superstructure, bulkwards, obstacles on the working deck and freeing ports or scuppers. These elements would affect the flow and water accumulation on deck and therefore could have an important influence in survivability. Again, if the scuppers at model scale are very small scale effects can appear. In such case larger openings that in reality are necessary. They can be dimensioned based on information about flow through orifices.

Taking into account these requirements the model has to be built with the following characteristics:

- The scale is selected as a compromise between the minimum necessary displacement to fit motor, batteries and instrumentation, the availability of and stock propeller similar the one fitted on the actual ship and the operational limits of the wavemaker. This resulted in scales around 1:8.
- The models were self-propelled and auto-piloted to eliminate any influence of cables in the model response to the waves.
- Most of the “ballast” weight was provided by the batteries in order to get the maximum testing time before recharging. These batteries were moved around the model inside to adjust inertias and GM.
- The general disposition of the ships has to be reproduced both in the inside as well as in the working deck and superstructure. Details like freeing ports, hatches, doors, ventilation, exhaust openings and so on had to be reproduced as exactly as possible but avoiding scale effects.
- The model has to be fully watertight during the seakeeping tests but has to allow easy access to the inside compartments for ballast redistribution to tests different load

conditions and possible modifications to study different damage scenarios.

Therefore the model was built with the following physical characteristics:

- Hull, decks, superstructure and bilge keels were made in FRP.
- Internal bulkheads and double bottom top were made in marine plywood 10 mm thick.
- Access to the interior was provided through commercial yacht hatches.
- Shafts for propeller and rudder were provided with rubber seals fitted on Teflon supports.
- Watertight sockets were fitted on the deck to allow easy charging of the batteries.

A female mould in two shells was used for the hull while a male mould was used for decks. This manufacturing system allowed the inside of the hull to remain opened for easy access to work in the bulkhead and double bottom installation as well as the arrangement of instrumentation.

All the moulds were made in extruded polystyrene with a five axis numerical controlled milling machine.

For the first time we used a new method of FRP lamination based on the use of PVC tape and epoxidic resins. This method happened to be very effective, allowing a shorter lamination time and a very precise and smooth finish of the surfaces.

The resulting final weight of the empty model is about 20% of the displacement (between 18 and 35 kg in these cases) leaving a good margin for instrumentation, batteries and weight adjustment.

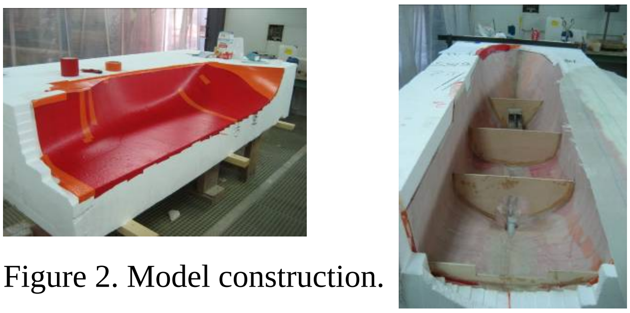

Figure 2. Model construction.

The model was kept watertight for the seakeeping tests. For the sinking tests, the openings suspected to be open at the time of capsizing were cut on the model. These openings corresponded to some hatches, doors and accesses to the engine room.

The permeability of each compartment was attained by adding foam blocks as adequate after discounting the volumes of batteries, bulkheads and so on.

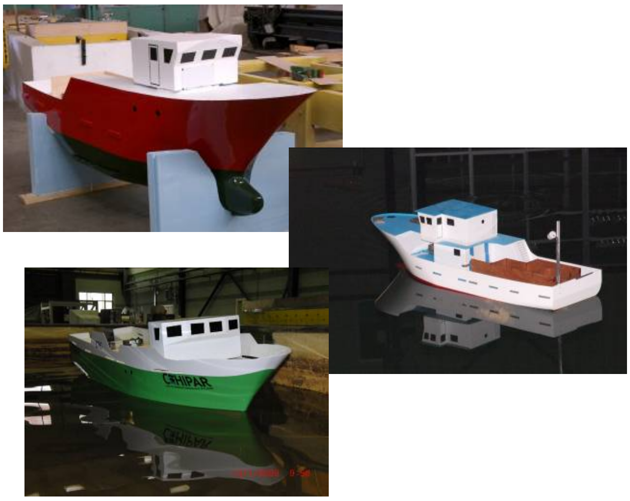

Figure 3. The ship models.

5. INSTRUMENTATION

The instrumentation used for the models had the objective of keeping the model in course at the adequate speed and record the information needed to interpret the results. It consisted in three principal points: propulsion and steering, navigation and data acquisition, and visualization of water flooding. If considered necessary systems to reproduce the wind forces can be included.

Propulsion and steering systems

A DC motor was used for the propeller, controlled by a motor driver. The steering system was made up of a rudder controlled by means of a special servomotor with high torque capabilities. Both systems were controlled by the navigation system. The rudder controller takes care that the rudder actuation rate is never larger than that corresponding to the real ship, so that the manoeuvring capacities are the same.

Navigation and data acquisition

Because of the purpose of these tests, a totally free model system was needed, so propulsion and steering systems were controlled by means of a radio signal. A commercial system developed for U.A.V. (Unmanned Aerial Vehicles) was adapted to our case. Figure 4 shows the main components operation of the system.

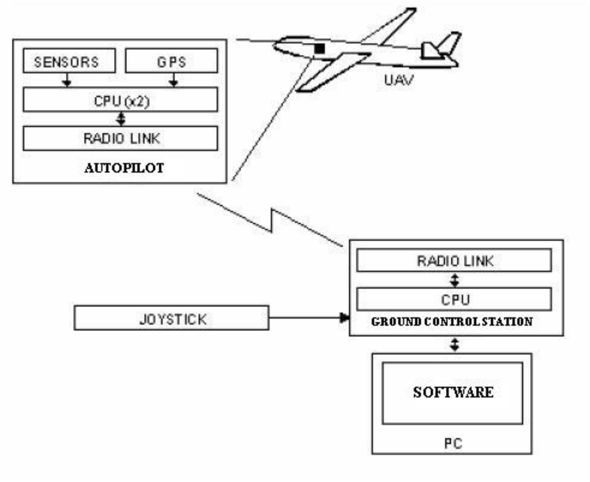

Figure 4. Sketch of the navigation and data acquisition system

The description of each part of the scheme is the following:

- UAV is the controlled vehicle. In this case it was the ship model.
- AUTOPILOT. It is a complete autopilot; it includes sensors (accelerometers, gyroscopes, magnetometers, and static and dynamic pressure sensors), a GPS, dual redundant processors, an interface to control servos and other peripherals, and a long-range radio link. The system was able to communicate up to 100 Km. On the other hand, GPS signal was not available inside the testing tank, so the “drift” provided by the system was not corrected by GPS as in outdoor uses: This is not a big problem as the tests duration is short and roll, the most important parameter in this case, was not affected by drift. In these tests the ship was controlled manually as is the typical way in bad seas, therefore this component was used only for data acquisition.
- GROUND CONTROL STATION. The ground control station relays all communications to any compatible ground control station software both in the downlink and uplink directions. Additionally, it can generate a manual control stream to pilot manually the model directly from a standard PC-style joystick, which was used in the tests to control the ship with the required trajectories.
- PC. A personal computer with the special software installed. This software processes all the information in order to control the ship and, besides, carries out the data acquisition. This software can control up to 16 servos simultaneously (in our case only the rudder and propeller engine servos were necessary), with a PID control where control constants could be changed in real time. Besides, it is able to recording up to an hour of video signal. This was used for an onboard camera to observe water flow on the working deck.

Deck flooding visualization.

As said before, the capability of the software for recording video was used record the flow on the working deck. The video signal was provided by a micro camera, whose small weight and volume were appropriated for the tests. It has a resolution of 440,000 pixels in 450 lines and a weight of a few grams with wireless transmission of the signal.

Wind effects reproduction.

If deemed necessary the wind forces can be simulated either in an static way by applying a fixed heel estimated from the wind speed and superstructure area distribution.

However there is another way to dynamically implement the wind in tests. At CEHIPAR, the usual procedure is to install onboard the model three fans, one longitudinal and two transverse ones, so that the three components of the wind can be reproduced: the longitudinal force, the transverse force, and the yaw moment. An example of this can be seen in Figure 5 of some tests carried out by CEHIPAR. The fans are computer controlled so that the correct forces are applied in each instant accordind to the ship's heading relative to the wind. This system also allows the introduction of a wind spectrum with includes low frequency variations as well as gusts.

Figure 5. Model fitted with fans for wind force simulation.

6. ENVIRONMENTAL CONDITIONS

In order to obtain information about the wave conditions at the time and site of the accident we have available two kinds of sources consisting in the Spanish net of oceanographic buoys and the data from hindcasting models. These are briefly described in the following.

There are two kinds of oceanographic buoy nets deployed around the Spanish shores; both of them are responsibility of the Spanish Harbour Authority. One is the Deep Water Net consisting of 13 buoys deployed in depths of between 200 and 800 meters. All of them are directional buoys.

The other is the Shore Buoy Net consisting in a total of 26 buoys, some scalar and others directional, which are anchored in shallower waters and therefore they are less useful unless the accident occurs near one of them.

The second source of information is called the WANA data and is based in the WAM numerical model. This is run routinely to obtain wave data estimations each 3 hours by the Spanish Harbour Authority and the Spanish Meteorological Agency. The calculations are made on a grid of 30 km resolution for the Atlantic Ocean and 15 km for the Mediterranean Sea. The model is run for forecasting purposes mainly but the data corresponding to the WANA system makes also use of actual measurements of pressure and wind field so that it can be considered as hindcasting results.

The data from these sources can be obtained in real time from Internet. But it can also be recovered later from the data bank maintained by the same two organisms.

If the accident occurred in somewhat restricted waters neither the deep water buoys nor the WAM model (which assumes deep water conditions) can be considered reliable. Therefore, unless we have a nearby shallow water buoy, we have to use propagation models to determine the wave conditions on the accident site from hindcast or buoy data. These models need as input not only the wave data at remote points but also the bathymetry of the zone and the current conditions. These can be estimated from the consecutive positions reported by the freely drifting distress buoy.

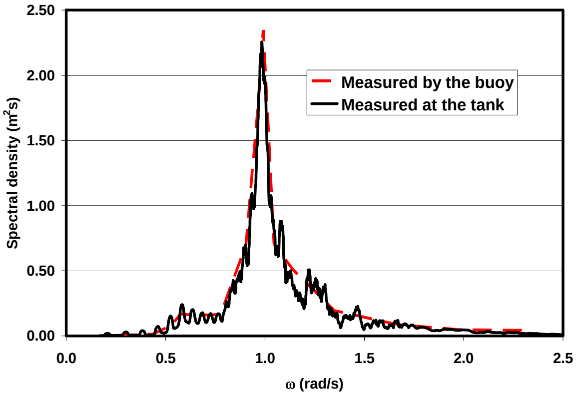

Figure 6. Example of wave spectrum generated at the laboratory.

Once the sea conditions are determined or guessed they have to be reproduced at the laboratory. The most straight forward procedure is to generate, with the wavemaker, random irregular waves based in the principle of linear superposition and with a spectrum equal to the one estimated from the available information. One example of the fidelity that can be attained in the reproduction of the wave spectrum can be seen in Figure 6.

The wave pattern generated can include directional dispersion whose characteristics can be obtained from the same sources as explained before or from empirical formulas based in wind speed and wind past history.

But the tests in irregular wave patterns are generally inconclusive. They are interesting because they give a feeling on the behaviour of the ship in the real conditions but they can not be considered definite regarding the causes of capsize because one can suspect that, if the sea was the cause of the capsize; it should have a low probability occurrence. Otherwise many ships had to capsize at the same sea conditions.

Therefore to have a good insight into the causes of the accident using irregular waves we should test the model for many hours and in different random sea simulations. As this is a time consuming task, we follow another alternative implying deterministic waves.

To this purpose, based on the information available (sea spectrum or just significant height and wave period) we make simulations to determine the zero crossing distributions of wave period and wave height. The simulations are based presently in linear theory and therefore they consist in the addition of many sinusoidal waves with random phases and amplitudes obtained from the wave spectrum.

One example of the results is given in Figure 7 where the waves had been classified in bins of 0.25 m for the heights by 0.25 s for the periods. The simulations allows us to choose waves that could have been the cause of the capsize. The selection is made based in several facts: the wave has to have an appreciable probability of occurrence (say 2%, which is arguable), it is not breaking and is near roll resonance at the encounter frequency or near zero encounter frequency if travelling in quartering or following seas.

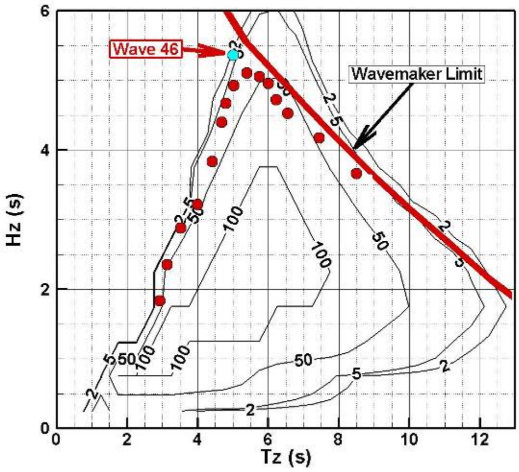

Figure 7. Example of wave period/height distribution for a given sea state. Probability of occurrence in three hours.

Of course we know that the ship will not encounter a regular wave pattern in the real sea and for this reason we do discard as realistic capsizes those that happen after more than two wave encounters except if we observe that the model is travelling with the wave as it is often the case.

The basin of CEHIPAR at the seakeeping laboratory is 150 m long by 30 meters wide with the wavemaker in the short side. This means that with a conventional wave generation system, the useful area for wave generation will be the area of 30 by 30 meters in the surroundings of the wave maker. But this can be increased by using the developments available at CEHIPAR which use the wall reflections allowing the generation of any wave pattern at any position of the tank with a good degree of approximation.

The method is based in considering the wave natural modes of the seakeeping tank, which depend on the tank width and the wave period. These natural modes are given generally by:

$$\eta = iDe^{-i\omega t}\sum_{m=0}^{N}\frac{c_m}{k_m}e^{ik_{xm}x}\cos k_{ym}y$$

where D is the wavemaker transfer function, y is the transversal coordinate, x is the longitudinal coordinate (along the largest dimension of the tank) and k_{xm} and k_{ym} are the wave numbers in each direction for each natural mode of the tank. They are given by:

$$k_{ym} = \frac{\pi\, m}{B}$$

Where B is the width of the wavemaker and m is an integer indicating the order of the natural mode. The longitudinal wave number is related to the transversal one by:

$$k_{xm} = \sqrt{k^2 - k_{ym}^2}$$

Where k is the absolute wave number. The method consists in determining the wavemaker motion that minimizes the difference between the desired wave in a given rectangular area and the wave generated according to linear theory. The number of natural modes given by the maximum value of m is kept below a value that avoids the generation of the so called “evanescent waves” (waves which decay exponentially away from the wavemaker) which complicate the solution of the problem without adding any appreciable contribution o the goodness of the wave pattern.

Sometimes the optimization is very good but results in excessive motions of the wavemaker. In such cases one can opt to minimize the wavemaker motion while keeping the wave error in the area of interest equal to some reasonable value. These problems can be solved by conventional least squares methods including Lagrange multipliers for the later case. The mathematical details can be found in Marón (1999 and 2009).

This is a kind of “deterministic” procedure to generate waves but has the drawback that the generated waves are regular. CEHIPAR is involved in a research to improve this method by generating nonlinear deterministic waves of large slope embedded into an irregular wave pattern. The study will deal also with the problem of determining the probability of occurrence of such episodic waves in a given sea state. This will allow us to tests the models in realistic large waves with a known probability of having developed in the real sea (see for example Clauss, 2007).

7. TEST PROCEDURE

Once the model is built and the wave conditions, load conditions, speeds, headings and deck arrangements are decided, the tests are started.

First the model is adapted for each load condition and deck arrangement. Special care has to be put in the adjusting of GM and rolling period. It is also important reproduce accurately the drafts as small changes in freeboard can be important from the point of view of water accumulation on deck.

Some preliminary tests are made in order to adjust the propeller rpm to get the desired speed.

We normally start by testing the model in irregular waves corresponding to those prevailing at the time of the accident; although we know that most probably the model will not capsize during these tests because the probability is low. But these tests are good to know the overall behaviour of the ship like the amount of roll, the tendency to broaching or the frequency of water shipping.

After that, deterministic regular waves are selected as explained before. We look for regular waves having a probability of at least 2% in 3 hours and concentrate in those waves with lengths similar to that of the ship or with an encounter period around the synchronism. Also dangerous are waves whose encounter period is near zero so that the loss of stability in the crest lasts for a long time.

In reality the ship will encounter only one or at most two consecutive such waves so that we put the model sailing in head seas into the waves and them make a quick turn to the desired heading. If the capsize happens in the first or second encounter or it is in very bad conditions after that, then we consider that the accident could had been produced by such kind of wave.

These tests are repeated varying several parameters in order to cover all the possible hypothesis compatible with the available information like: different GM's, different speeds and headings, different wave heights or different deck arrangements.

8. CONCLUSIONS

Scale model tests can be a valuable tool to investigate the causes of accidents of fishing vessels, especially if due to the lack of survivors no witnesses are available.

The tests can help to evaluate whether or not the sea conditions could be the cause of the accident and if so under which circumstances the capsize was more probable. This happened with two of the models tested were we conclude that there was an appreciable probability that waves produced the capsize. But for one of them this could only be possible if some circumstances were existing at that time, like a low freeboard aft implying that two aft tanks were filled.

In other case the tests demonstrated that, although the crew reported flooding of the working deck, this could not be the only cause of the accident.

The tests also give the Authorities clues about which regulation modifications or recommendations to the fishermen can improve the safety of their work.

9. REFERENCES

Borlase, G., 2002, "Research Opportunities Identified during the Casualty Analysis of the Fishing Vessel **Artic Rose"**, Proceedings of the 6th International Ship Stability Workshop, Webb Institute, 14-16 October 2002.

Clauss, G. F., A. Kauffeldt & K. Jacobsen, 2007, "Longitudinal Forces and Bending Moments of a FPSO", OMAE 2007.

Grochowalski, S., 1989, "Investigation into the Physics of Ship Capsizing by Combined Captive and Free Running Model Tests", SNAME Transactions, 1989, pp 169-212.

IMO, "Guidance to the master for avoiding dangerous situations in following and quartering seas", MSC/Circ. 707.

Marón, A., 1999, "Optimization of Wave Generation for Seakeeping Tests". Wave generation '99, International Workshop on Natural Disaster by Storm Waves and Their Reproduction in Experimental Basins, Kyoto.

Marón, A., 2005, "Investigation on the sinking of a fishing vessel in following seas", CEHIPAR report OTI-2236-CM-1 (in Spanish).

Marón, A., 2009, "Optimización de Generadores de Olas para Ensayos de Comportamiento en la Mar" (Wavemaker Optimization for Seakeeping Tests"), Ph. D. Thesis presented at the Madrid School of Naval Architects.

USCG, 2003, "Sinking of the Uninspected Fishing Vessel Artic Rose, Official Number 931446, in the Bearing Sea on April 2, 2001.

Womack, J. and Johnson, B., 2005, "A Systematic Study of Wave Phasing on Righting Arm Curves for Fishing Vessels", SNAME Transactions, 2005.