Small fishing vessels study and modelling for the improvement of the behaviour in extreme seas

Antoine Pagès, *Sirehna*, antoine.pages@sirehna.com

Jean-Jacques Maisonneuve, *Sirehna*, jean-jacques.maisonneuve@sirehna.com

Clève Wandji, *Bureau Veritas*, cleve.wandji@bureauveritas.com

Philippe Corrignan, *Bureau Veritas*, philippe.corrignan@bureauveritas.com

Benoît Vincent, *Ifremer*, benoit.vincent@ifremer.fr

ABSTRACT

Commercial fishing is one of the most dangerous primary activities. Most of the 24000 yearly accidents identified by IMO are occurring on small vessels. The French SOS-Stabilité research project aims at better knowing and modelling dynamic stability issues occurring on small fishing vessels (12 to 24 m), prior to the development of solutions for improving their behaviour, through the evolution of the ship design and through the design of appropriate embedded systems. This paper presents the first part of the project: sea and model tests, development of a ship behaviour time-domain simulator (including fishing gear modelling capabilities) and first validation of this simulation tool.

Keywords: *SOS-Stabilité, time-domain simulator, small fishing vessel, dynamic stability, non-linear effects*

1. INTRODUCTION

The French SOS-Stabilité research project[1] aims at better knowing and modelling dynamic stability issues occurring on small fishing vessels, prior to the development of solutions for improving their behaviour, through the evolution of the ship design and through the design of appropriate embedded systems. The developments undertaken within the scope of the project are made in connection with existing regulations about small fishing vessels.

During the first part of the project, sea trials and model tests with a 23 m trawler have been carried out and have helped developing and validating the general models implemented in a ship behaviour time-domain simulator, and more specifically the fishing, sea-keeping and manoeuvrability models.

The sea trials consisted in measuring various loads (rudder, trawler lines, etc.) and the ship behaviour at sea. The basin trials consisted in the study of the ship behaviour in following, quartering and beam seas, with and without speed.

The aim of the time-domain simulator is to model the dynamic behaviour of ships in rough seas, with small calculation time, to enable systematic variations and analyses of small fishing vessels safety with relation to their dynamic stability. The main focus is the phenomena observed in following seas, like broaching-to, involving a strong coupling between the ship's degrees of freedom and strong variations of its roll and yaw stability characteristics. The

[1] SOS-Stabilité, project supported by the French ministry of industry, regions Bretagne, PACA and Pays de la Loire; improvement of small fishing vessels safety; partners: Bureau d'études Mauric, Bureau Veritas, IFREMER, Institut Maritime de Prévention, Société des Etablissement Merré, PRINCIPIA SAS, SIREHNA.

stability in operation at low speed, with the fishing gear active, is also addressed.

2. REGULATION

A review of the relevant regulations of Bureau Veritas (BV) rules, European Union (EU) and international (IMO) rules, for dynamic stability on fishing vessels was conducted. Apart from aspects strictly related to the stability, the regulations on equipment that may impact on the stability of fishing vessels have also been reviewed. Moreover, in addition to existing recommendations and regulations, international developments in progress on these issues were included in this study.

Nowadays, there are no mandatory international regulations concerning the stability of fishing vessels. The Torremolinos protocol provides provisions for vessels of length greater than 24 m, but it has not yet entered into force. However, this protocol has been integrated into EU directive, and it is mandatory for all European states.

French regulations on fishing vessels are very thorough, covering all sizes of vessels, which are divided into three categories: less than 12 m (division 227), from 12 to 24 m (division 226) and over 24 m (division 228, which is the French transcription of the EU directive).

It is worth emphasizing some specific points in the above mentioned regulations.

- The current intact stability criteria are mainly related to quasi-static notions associated with the stem and freeboard heights, with areas of righting lever curve and initial metacentric height. The dynamic stability phenomena should also be integrated in the intact stability code in 2014, through the second generation criteria (but these criteria are not specific prior to fishing vessel).
- Downflooding angles are extremely important. They are related to the definition of enclosed spaces, whose misinterpretation led to disaster, especially with the effect of freeing ports in enclosed spaces.
- The influence of free surface effect is treated in a simplified way. On the other hand damage stability is not considered for fishing vessels (there are just a few recommendations in the Torremolinos convention on this subject), although fishing vessels have already been lost due to insufficient stability after damage.
- The influence of underwater obstacles is considered only in the French regulations for vessels under 24 m and in a very simplified way.
- Stability criteria assessments are made under some assumptions (closing openings, automatic limitations of the load in the fishing rope, etc…) which, if they are not fulfilled by the crews, can lead to loss of stability.
- There are no performance criteria for course control systems on swell.

3. THE TARGET SHIP

The ship chosen for the various tests (both sea and model trials) is the 23m trawler ship “Anthinéas”, build in 1991 in France. Its home port is Les Sables d’Olonne. Its main particulars are given in Table 1 and a side view is shown below.

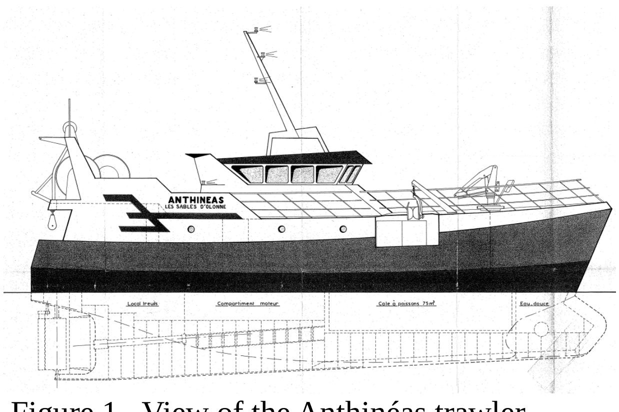

Figure 1 View of the Anthinéas trawler.

The fishing gear is made up of twin trawls towed by three warps. It is used for bottom trawling.

The main reasons that have led to the choice of this trawler are the fact that its dimensions fit in the aimed dimensions of the SOS-Stabilité project (12 to 24 m), the closeness of its home port (making instrumentation installation and onboard engineers turnover easier) and the will of its owners to cooperate on this project.

4. EXPERIMENTS

4.1 Sea trials

The main objective of the sea trials was to gain some experience about the fishing environment, the behaviour of a standard trawler and the possible measurements onboard. Therefore the sea trials were carried out onboard an operational ship with the will not to interfere with the crew normal activities; in particular this implied some restrictions about the control of the trials conditions, the embedded measurement systems and their ease of use.

Instrumentation. The instrumentation installed onboard can be broken down into four groups.

- “Movements” group: measurement of the ship movements (attitude, speed over ground, accelerations, angular speeds) and ship trajectory (heading, latitude, longitude).
- “Controls” group: measurement of the propeller pitch, engine speed, steering angle, rudder forces.
- “Warps” group: measurement of the forces and orientation of the three warps.
- “Environment” group: measurement of the wind speed and direction, sea-state estimation.

Trials. During the trials, the ship sailed in the Bay of Biscay, close to the shore (about 10 nautical miles), between Saint-Gilles-Croix-de-Vie and Oléron Island during 12 days in September 2009. Except during one day (during which the sea state was 4), the sea state encountered was not greater than 2.

Several kinds of trials were carried out both during fishing (usual manoeuvres) and during voyage (dedicated tests). The displacement during the trials varied from 206 t to 182 t. The main variations were the oil, fresh water and catch weight.

During fishing, the following tests were carried out:

- action of fishing, with or without turning;
- hauling action;
- veering out action.

During voyage, the following tests were carried out:

- turning;
- roll decay tests;
- deceleration;
- speed tests.

4.2 Model tests

One of the SOS-Stabilité project objectives is the identification and modelling of the most extreme and critical conditions for the ship stability. Therefore, model tests were carried out in order to be able to control the environment, and particularly to generate rough waves, and to measure the corresponding non-linear ship response.

Two main campaigns were carried out:

- the first one with zero-ship-speed in order to study beam seas with varying down-flooding conditions and following seas while fishing; it took place at the wave tank at Ecole Centrale de Nantes (ECN, France), which is 50 m long, 30 m wide and 5 m deep; the wave generator can create regular and irregular waves up to 0.3 m height;
- the second one with forward speed and

following seas; it took place at the Seakeeping and Maneuvering Basin at MARIN (Netherlands), which is 170 m long, 40 m wide and 5 m deep; the wave generator can create regular and irregular waves up to 1 m height.

A complementary outdoor campaign was also carried out without waves in order to set the autopilot, to study the ship behaviour in calm water and to check its performances before the tests in MARIN.

Model description. The model used for the basin trials is a model of the Anthinéas trawler at 1/11 scale The chosen displacement is 250 t at full scale, corresponding to the departure loading case with the worst initial stability according to the stability characteristics. Another loading case was also used during the MARIN tests, derived from the latter by simply raising the ship centre of gravity, which led to a “damaged” GM.

The main particulars for the chosen displacement at model scale and full scale are shown in Table 1.

The model ship is fitted with an electric engine with a maximum power of 390 W; the maximum shaft rotation obtained is 2000 RPM.

In order to model the full scale ship roll behaviour as well as possible, the model ship is fitted with bilge keels with dimensions corresponding to those of the full scale ship.

Since downflooding is one of the main concerns of the basin trials, the model ship is also fitted with openings on the main deck, consisting of scuppers to evacuate green water and of possible entrance for downflooding.

The study of the behaviour of the ship while fishing is also a great concern. Therefore several fishing gear towing points are available. The fishing gear is modelled by a simple bungee, of which the stiffness and damping are known.

Scale	Model	Full
Length overall (m)	2.08	22.89
Length between perpendiculars (m)	1.85	20.39
Overall breadth (m)	0.64	7.04
Forward draught (m)	0.27	2.97
Aft draught (m)	0.345	3.8
Light displacement (t)	-	173
Displacement (t)	0.188	250
Possible downflooding volume (L)	50	66550
Nominal GM (m)	0.0657	0.723
Damaged GM (m)	0.046	0.506

Table 1 Main particulars of Anthinéas trawler at model and full scale.

Instrumentation. The various measurements and recording systems used during the model tests were:

- a trajectography system allowing to measure the 6 degrees of freedom of the ship;
- an inertial unit measuring the ship attitude;
- dynamometers allowing to measure all the relevant forces (propulsion thrust and torque, rudder screw, fishing gear forces);
- capacitive probes to measure the relative water height at three points of the ship;
- 2 cameras, shooting different places depending on the tests;
- a GPS antenna to measure the ship speed and position (for the outdoor tests only).

Zero-speed tests. Three kinds of tests were carried out at zero-speed:

- beam sea with varying wave period;
- following sea with the ship hold still by cables (bungees) with varying wave period and varying engine speed;
- ship hold still by cables (bungees) without waves and qualitative simulation of the snagging of a fishing gear.

Outdoor tests. Outdoor tests on the Erdre River (near Nantes) were carried out in order to study the ship behaviour in calm water (manoeuvrability, resistance, acceleration, deceleration), check the propulsion capabilities and set the autopilot. The various tests carried out were:

- ship speed obtained for several engine speeds in order to draw the propulsion calibration curve;
- acceleration test to work out the time and distance to sail at maximum speed and the speed variation in time;
- deceleration speed to work out the time and distance for the ship to stop and the speed variation in time; this test can help getting access to the ship resistance;
- turning circles for various ship speeds and rudder angles to help getting access to the manoeuvring coefficients.

Tests with forward speed. Three kinds of tests were carried out with forward speed:

- regular beam sea at 2 forward speeds (voyage and fishing speeds) with wave period corresponding to the ship roll period;
- following sea at varying wave period (slightly overtaking waves, slightly overtaken waves, maximum wave camber and high wave period);
- following quartering sea (30° and 45°) at varying wave period (slightly overtaking waves, slightly overtaken waves and maximum wave camber).

During all the tests, the ship steering was controlled by an autopilot.

5. TIME-DOMAIN SIMULATION

The time-domain simulator developed in the scope of the SOS-Stabilité project is meant to be a simplified simulator allowing to take into account the forces of interest while keeping low calculation time; this must enable to use the simulator in an efficient way for quick design assessment and systematic variations, … The modelling of the forces implemented in the simulator are detailed below.

5.1 Description, capabilities, method

The simulator is made up of a block solving the dynamics equations for a six degree of freedom solid body and of various modules modelling the external forces (propulsion, resistance, manoeuvrability, fishing, etc.). A specific feature of the simulator is that non-linear effects are taken into account in order to model large ship motions correctly, but with simplified approaches. In particular, the hydrostatic and hydrodynamic Froude-Krylov effects as well as roll damping are modelled in a non-linear way.

Basic models. The external forces implemented in the simulator are listed below.

- Propulsion: propeller thrust depending on the propeller rotation speed and propeller pitch and on the ship speed of advance; the module coefficients are determined based on known, experimental or estimated data.
- Resistance: longitudinal and vertical forces and pitch moment depending on the ship relative speed of advance, based on statistical models (Holtrop, 1982, 1984).
- Manoeuvrability: longitudinal and lateral forces and yaw moment depending on the ship relative speed with respect to water (taking drift and wave orbital velocity into account) and yaw speed; the manoeuvrability model used is a calm water “classical” model close to the one proposed by Lewis (1989).
- Rudder: specific rudder module taking into account the propeller slipstream (Brix, 1993) and the wave orbital velocity at the rudder location.
- Lifting surfaces: general module to take into account the effect of lifting surfaces, like bilge keels, by the mean of lift and drag coefficient.
- Hydrostatic and hydrodynamic (incident wave) model: computation of the water pressure around the ship hull (Froude-Krylov) neglecting diffraction forces; the model ensures that non-linearities due to extreme motions are accounted for; some more details are given further.
- Weight: forces due to gravity.
- Radiation: only the added inertia and radiation damping coefficients are accounted for, obtained by a frequency-do-

main calculation.

- Damping: heave, roll and pitch linear damping and roll quadratic damping coefficients, obtained from experimental or empirical (Himeno, 1981) data; the coefficients can be dependent on the ship speed of advance.
- Wind: longitudinal and lateral forces and yaw moment depending on the ship relative speed with respect to wind and yaw speed.
- Fishing: several options, detailed further, are available to compute fishing forces; the snagging of a fishing gear can also be simulated.
- Flooding: forces due to green water and its propagation within the various ship tanks (engine room, ship room…); the water dynamics within the compartments (sloshing) are not directly accounted for.

Regular and irregular waves can be used within the simulator. Irregular waves are modelled through a superposition of regular waves (Airy model). Therefore a wave system is defined by the spectral characteristics of each of its components: amplitude, period, phase and propagation direction. Cross seas can also be used.

An autopilot block can also be used to control the ship heading. The autopilot can therefore be changed easily. This feature is needed in the scope of the SOS-Stabilité project since one of the goal of this project is the improvement of the ship control, especially in following seas.

<u>Hydrostatic and hydrodynamic model.</u> The water pressure around the ship hull (Froude-Krylov) is computed taking into account the relative position of the ship against the free surface (including incident waves).

The ship is modelled by a simple mesh so that the total pressure forces are obtained by integration of the pressure over all the immerged cells. A mesh example is shown in the figure below.

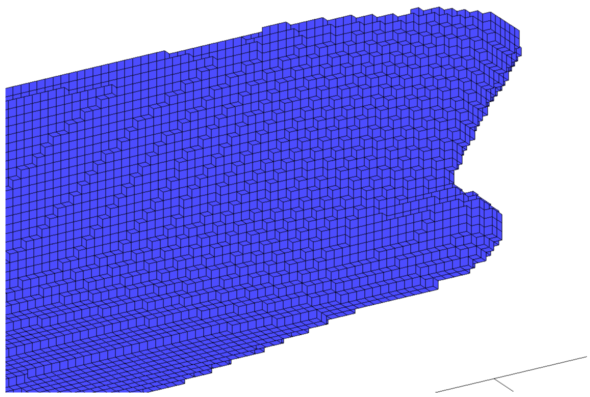

Figure 2 View of the forward part of the Anthinéas mesh.

The pressure used to compute the Froude-Krylov forces integrates the dynamics due to waves; this dynamic part depends on the spatial and temporal position. The free surface is supposed not to be modified by the body, that is the pressure variations due to the presence of the body (diffraction forces) are neglected.

This model ensures that the real immerged part of the ship is taken into account in the computation of hydrostatic and incident wave forces whatever the position and attitude of the ship, and therefore ensures that non-linearities due to extreme motions are accounted for.

<u>Fishing.</u> The fishing forces can be modelled in two different ways, depending on the intended result precision and computational time.

The most complete and precise method is the coupling of the simulator with a dedicated trawl gear simulation software, DynamiT, developed by Ifremer. This tool fully models the trawl gear (bottom or pelagic trawls, single, twin or more trawls, panels…) and simulates the dynamics of the fishing gear. Netting material, made of meshes, is modelled by a cylinders-net. Netting and other elements (floats, ground gear, doors …) are modelled by damping forces (drag and lift), hydrostatic forces and inertia forces that are calculated along the deformation of the structure in the water by an implicit time solver. Water motion is supposed not to be affected by the gear motion. Interaction with the seabed is modelled with Newton friction law. Obstruction on the seabed, one of the main event that can strongly affect the trawler, can be simulated by forcing the kinematics of any element of the trawl gear (for instance a part of the ground gear speed becoming null). Thus, for example, it is possible to analyse the damping effect of trawl doors onto the warp tension during the obstruction process. The outputs are all the information about the fishing gear geometry (positions, openings, door to door distance…) and forces (rig tensions, towing force…). The results obtained by coupling the ship simulator and trawl gear simulator are used to develop and improve a simplified fishing model to be implemented directly within the ship simulator.

Within the simplified model, the fishing gear consists in one bar (2 for twin trawls), representing the trawl, linked to the ship by 2 warps (3 for twin trawls), which are modelled by a catenary. A sketch of this modelling is shown below.

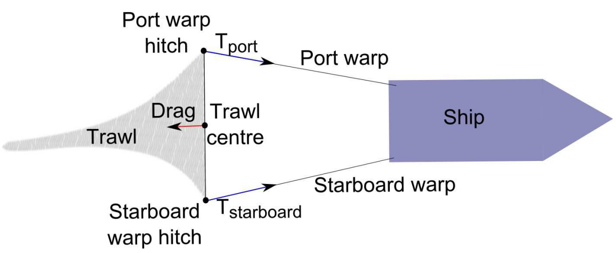

Figure 3 Fishing gear simplified model.

In this way, each fishing gear is defined by a mass-stiffness system with 3 degrees of freedom: longitudinal and transverse translations and rotation about the vertical axis, the trawl depth being considered constant. The loads applied to each fishing gear are then the warps tensions, the trawl hydrodynamic resistance and the friction of the trawl on the seabed. These loads are added to the other external forces for the resolution of the dynamics equations.

5.2 Validation

The validation of a simulator is a very important step to gain confidence in its results. Several qualitative and quantitative validations have been carried out, in particular for non-linear phenomena:

- qualitative validation of parametric roll using previous trials carried out by Sirehna on a 80 m fishing vessel (Maisonneuve, 2007);
- qualitative validation of broaching-to using model trials with a Japanese fishing vessel (Umeda et al., 1999, Umeda, 2000).
- quantitative validation using the trials carried out during SOS-Stabilité project and described above.

Parametric roll. Sea trials have been carried out by Sirehna (Maisonneuve, 2007) on an 80 m fishing vessel prone to parametric roll. The environmental conditions encountered during the trials have been reproduced in the simulator. The trials movements and the simulator results are shown in the figures below. Heave is positive downwards, roll is positive to starboard and pitch is positive bow up. The arrows on the graphs indicate a minimum in heave, which means the ship is on a wave crest.

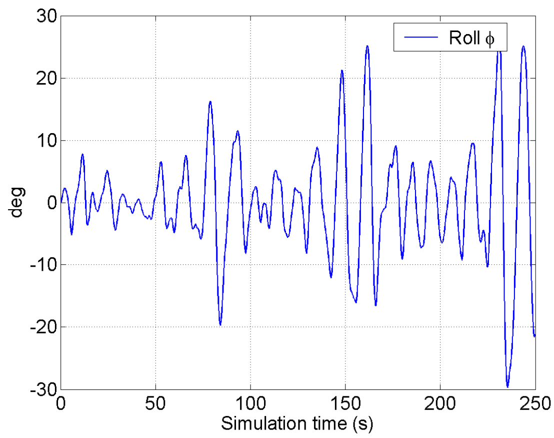

Figure 4 Roll variations (simulator).

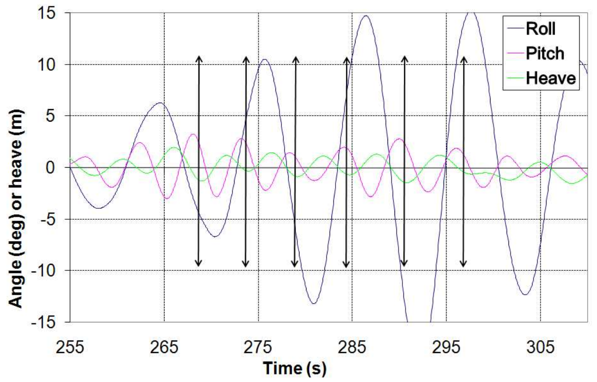

Figure 5 Heave, roll and pitch variations (trials).

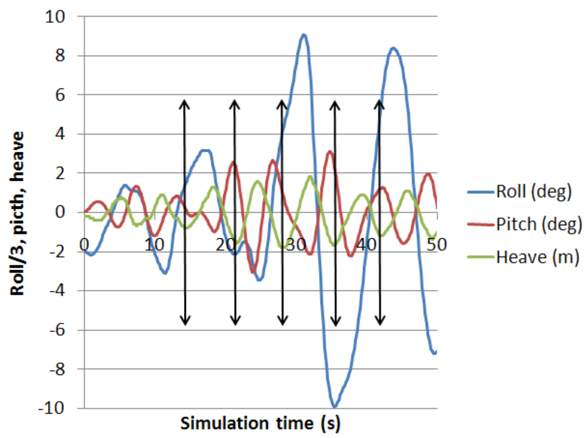

Figure 6 Heave, roll and pitch variations (simulator); note: roll has been divided by 3.

It can be seen that parametric roll is obtained with the simulator (apparition of "bursts" of large roll); this non-linear phenomenon is obtained "naturally", without triggering it. The phases between heave, roll and pitch are very similar for trials and simulation: the instants when the ship is on a wave crest happen slightly before the instants of roll extremum. The main difference between trials and simulation is the greater amplitude of the movements, particularly roll, for simulation. A reason to that difference can be the use of only linear damping coefficients within the simulator (no quadratic coefficients have been used in order to simplify the data setting).

Broaching-to. Basin trials have been carried out by Umeda (1999, 2000) on a 35 m Japanese fishing vessel (at 1/15 scale) prone to broaching. The trials were carried out with regular waves.

The test-case has been modelled in the simulator, with three wave conditions (increase in wave height and period from the first one to the third one and variation of wave angle) all three conditions led to capsizing due to broaching-to during Umeda's trials. The following figures show the Euler angles variations obtained with the simulator for the first and third wave conditions.

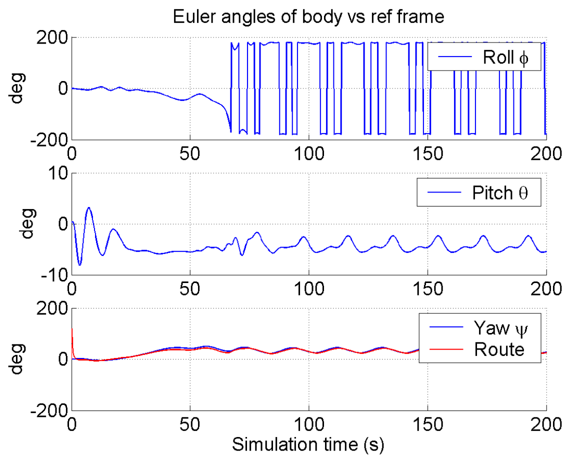

Figure 7 Euler angles obtained with the simulator for the first wave conditions.

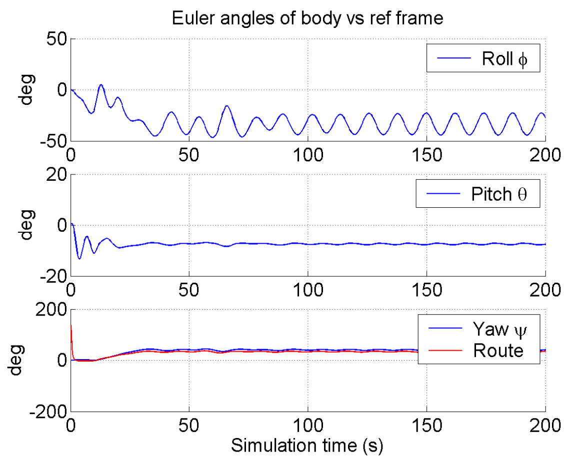

Figure 8 Euler angles obtained with the simulator for the third wave conditions.

The three simulated cases lead to broaching-to (the yaw angle deviates of about 40° from its initial value and large roll angles are obtained), but only the first two lead to capsizing due to broaching-to. These results show that broaching-to is qualitatively obtained by the models implemented in the simulator; these models need to be improved to obtain good quantitative agreement with experiments.

Validation using sea trials and model outdoor tests. The sea trials and the model outdoor tests can be used to validate the calm water behaviour of Anthinéas (validation of the modules implemented in the simulator and setting of the coefficients for the specific ship chosen for the study). The figures below show a comparison of experimental and computed results for some elementary validations; the experimental values have been converted from model scale to full scale.

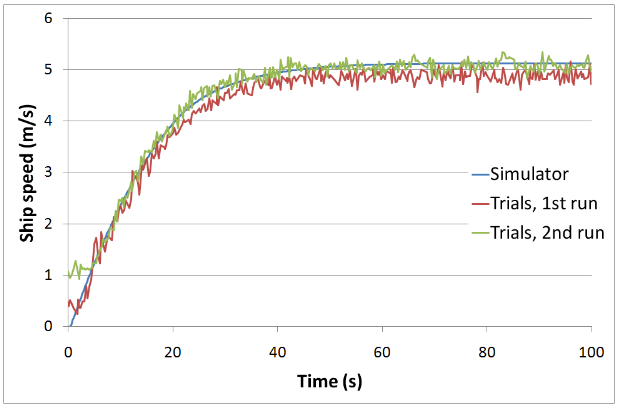

Figure 9 Ship speed variation during acceleration (model tests / simulator).

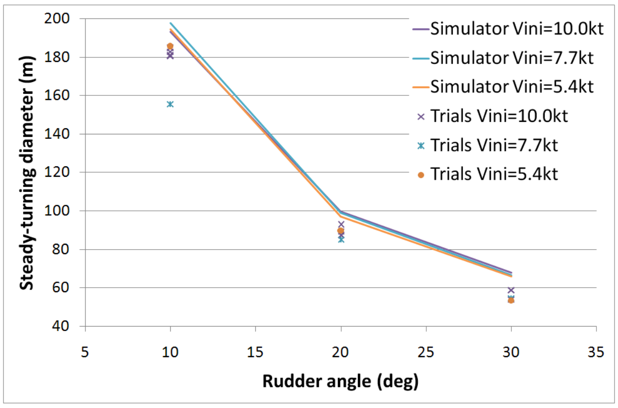

Figure 10 Steady-turning diameter for 3 rudder angles (model tests / simulator).

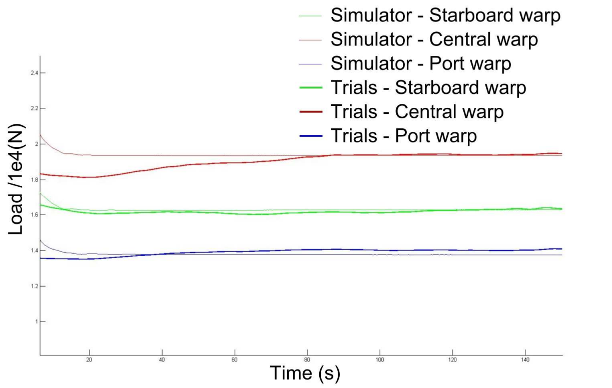

Figure 11 Warp loads (sea trials / simulator); trial signals have been filtered.

The simulation results are close to the experimental ones for the elementary tests shown here as well as for the others: the modelled ship behaviour is meeting the one observed during the trials.

Validation using basin trials. Once the Anthinéas parameters are set, the basin trials can be used to validate the modules involved in the ship behaviour in waves (Froude-Krylov forces, roll quadratic damping, …). The figures and tables below show a comparison of experimental and computed results for some of the trials carried out in ECN basin; the experimental values have been converted from model scale to full scale.

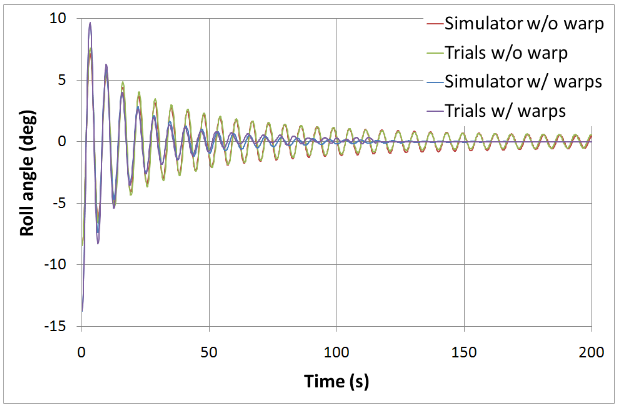

Figure 12 Roll decay tests with and without warps, without forward speed.

Wave parameters			Trials response amplitudes			Simulator response amplitudes		
Wave period (s)	Wave height (m)	Run type	Roll (deg)	Pitch (deg)	Heave (m)	Roll (deg)	Pitch (deg)	Heave (m)
6.30	1.1	Roll resonance	14.0	0.7	1.2	14.5	2.0	1.5
6.30	2.2	Roll resonance	24.0	2.7	2.5	24.0	3.0	2.5
6.30	3.3	Roll resonance	29.0	3.7	3.7	31.0	2.0	3.3
9.95	5.5	High period	13.3	3.1	4.9	13.5	1.0	5.8
9.95	9.9	High period	18.5	2.2	10.1	20.0	2.0	10.7

Table 2 Roll, pitch and heave amplitudes with various regular beam seas without forward speed.

The results show that the ship behaviour for beam seas without speed is correctly modelled by the simulator. Further use of ECN trials is still to be done, especially tests implying following seas, warps, green water and flooding.

The following figures now show a comparison of experimental and computed results for some of the trials carried out in MARIN basin; again, the experimental values have been converted from model scale to full scale.

The comparison of trials and simulator results show good qualitative agreement. Some quantitative improvements need to be done:

- for quartering sea, drift speed obtained with the simulator is a bit lower, leading to a phase shift between roll signals;
- movements in following sea tend to be overestimated with the simulator.

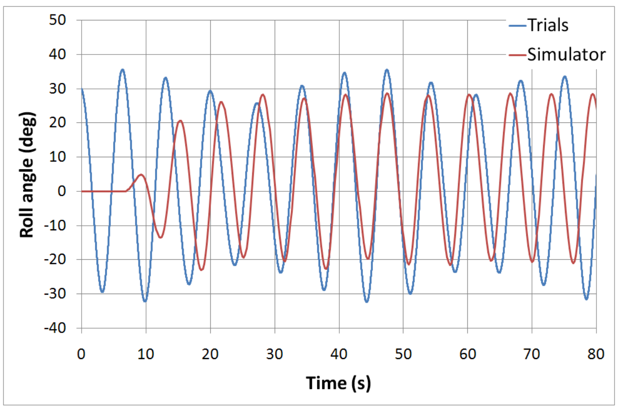

Figure 13 Roll variation for regular beam sea (H_{wave}=3.3 m, period=ship roll period) with forward speed (V=10 kt).

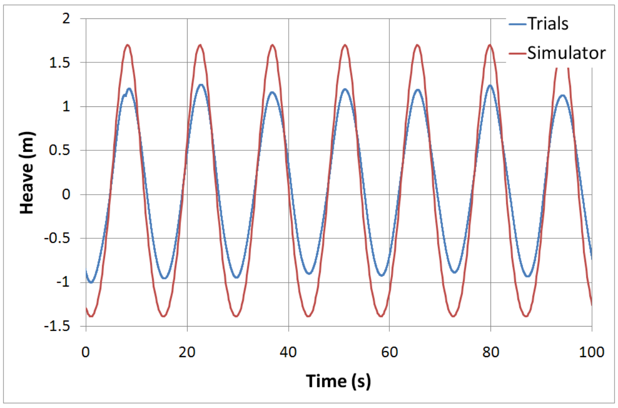

Figure 14 Heave variation for regular following sea (H_{wave}=3.3 m, T=9 s) with forward speed (V=10 kt).

Further use of the MARIN trials is still to be done, especially tests implying following and quartering seas with low encounter period.

6. NEXT STEPS

The trials, especially those carried out in ECN and MARIN, need to be further analysed and used for the simulator validation.

In addition to this work, sea trials with a 1/3 scale model and developments of solutions to improve the small fishing vessels behaviour are planned before the end of the SOS-Stabilité project.

6.1 Large scale trials platform

High sea states are very critical conditions for the seakeeping of small fishing vessels, particularly for quartering and following seas. To observe these conditions and the corresponding ship behaviour, nor basin trials neither sea trials are ideal. Basin trials need very sophisticated equipment to avoid scale effects and recreate realistic environmental conditions. Sea trials on full scale ships are often limited by the possible embedded instrumentation (which must not be inconvenient for the usual operation of the ship), the crew safety and the ability to vary the ship configuration.

Therefore, to avoid the disadvantages of basin and full scale trials, a 1/3 scale model of the Anthinéas has been built and must be used for sea trials. The so-called “large scale trials platform” has been designed to easily vary some of its characteristics (loading, stability, fishing gear towing points, free surface tanks …) and is unmanned, totally waterproof and unsinkable so that it can meet extreme sea states possibly leading to capsizing.

6.2 Development of safety improvement solutions

The experiments and the simulations presented above and those to be carried out in the future enable to gain knowledge of the small fishing vessels behaviour in extreme seas. From this knowledge, some leads for the improvement of these ships safety can be drawn.

A first lead is the use of suitable passive (detection of dangerous conditions and warning of the crew) and/or active (specific autopilot and control of the fishing gear) embedded systems. Such embedded systems are being developed within the project.

Another lead is the development of innovative ship designs, fishing gear designs and ship-fishing gear interfaces. Such developments are also carried out within the project.

6.3 Exploitation of project results

The final step of the project is the dissemination of the gained knowledge. The exploitation of the results will be done by:

- the setting up of specific education / training programs dedicated to the safety of fishing vessels in extreme seas;
- the definition of operational limitations, recommendations and links with regulations for the behaviour of small fishing vessels in extreme seas.

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