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An Autonomous Scale Ship Model for Parametric Rolling Towing Tank Testing

M. Míguez González, A. Deibe, F. Orjales, B. Priego and F. López Peña

Integrated Group for Engineering Research, University of A Coruña, Spain
Corresponding author: M. Míguez González <mmiguez@udc.es>

Abstract

This chapter presents the work carried out for developing a self-propelled scale ship model for model testing, with the main characteristic of not having any material link to a towing device to carry out the tests. This model has been fully instrumented in order to acquire all the significant raw data, process them onboard and communicate with an inshore station.

Keywords: Ship scale model, autonomous systems, data acquisition, parametric resonance, towing tank tests.

3.1 Introduction

Ship scale model testing has traditionally been the only way to accurately determine ship resistance, propulsion, maneuvering and seakeeping characteristics. These tests are usually carried out in complex facilities, where a large carriage, to which the model is attached, moves it following a desired path along a water tank.

Ship model testing could be broadly divided into four main types of tests. Resistance tests, either in waves or still water, intended to obtain the resistance of the ship without taking the effects of its propulsion system into consideration. Propulsion tests aimed at analyzing the performance of the ship propeller when it is in operation together with the ship itself. Maneuvering tests the objective of which is to analyze the capability of the ship for carrying

out a set of defined maneuvers. And finally, seakeeping tests aimed at studying the behavior of the ship while sailing in waves [1].

The former two tests are carried out in towing tanks, which are slender water channels where the model is attached to the carriage that tows it along the center of the tank. The latter two, on the other hand, are usually performed in the so-called ocean basins where the scale model can be either attached to a carriage or radio controlled with no mechanical connection to it.

However, there exist certain kinds of phenomena in the field of seakeeping that can be studied in towing tanks (which are cheaper and have more availability than ocean basins) and that are characterized by showing very large amplitude nonlinear motions. The interactions between the carriage and the model due to these motions, which are usually limited to a maximum in most towing tanks, and the lack of space under the carriage, reduce the applicability of slender channels for these types of tests.

One of these phenomena is that of ship parametric roll resonance, also known as parametric rolling. This is a well-known dynamical issue affecting ships, especially containerships, fishing vessels and cruise ships, and it can generate very large amplitude roll motions in a very sudden way, reaching the largest amplitudes in just a few rolling cycles. Parametric roll is due to the periodic alternation of wave crests and troughs along the ship, which produce the changes in ship transverse stability that lead to the aforementioned roll motions.

Resonance is most likely to happen when the ship sails in longitudinal seas and when a certain set of conditions are present, which include a wave encounter frequency ranging twice the ship's natural roll frequency, a wavelength almost equal to the ship length and a wave amplitude larger than a given threshold [2].

Traditionally, parametric roll tests in towing tanks have been carried out by using a carriage towed model, where the model is free to move in just some of the 6 degrees of freedom (typically heave, roll and pitch, the ones most heavily influencing the phenomenon) [3, 4]. However, this arrangement limits the possibility of analyzing the influence of the restrained degrees of freedom [5], which may also be of interest while analyzing parametric roll resonance, or it may interfere on its development.

The main objective of the present work is to overcome the described difficulties for carrying out scale tests in slender towing tanks where large amplitude motions are involved, while preserving the model capabilities for being used in propulsion (free-running), maneuvering and seakeeping tests.

This has been done by using a self-propelled and self-controlled scale model, able to freely move in the six degrees of freedom and to measure, store and process all the necessary data without direct need of the towing carriage. In addition, the model could be used for any other tests, both in towing tanks or ocean basins, with the advantage of being independent of the aforementioned carriage.

The type and amount of data to be collected is defined after taking into consideration the typology of tests to be carried out. Taking into account that all three, propulsion, maneuvering and seakeeping tests should be considered, all the data related with the motion of the ship, together with those monitoring the propulsion system and the heading control system, have to be collected. Moreover, a processing, storage and communication with shore system was also implemented and installed onboard.

Finally, the results obtained by using the model in a test campaign aimed at predicting the appearance of parametric roll, where a detection and prevention algorithm has been implemented in the onboard control system, are presented.

3.2 System Architecture

The first implementation of the proposed system has been on a scale ship model that has been machined from high-density (250 kg/m^3) polyurethane blocks to a scale of 1/15th, painted and internally covered by epoxy reinforced fiberglass. Mobile lead weights have been installed on supporting elements, allowing longitudinal, transverse and vertical displacements for a correct mass arrangement. Moreover, two small weights have been fitted into a transverse slider for fast and fine-tuning of both the transverse position of the center of gravity and the longitudinal moment of inertia.

The propulsion system consists of a 650W brushless, outrunner, three-phase motor, an electronic speed control (ESC) and a two-stage planetary gearbox, which move a four-bladed propeller. The ESC electronically generates a three-phase low voltage electric power source to the brushless motor. With this ESC, the speed and direction of the brushless motor can be controlled. It can even be forced to work as a dynamic brake if need be. The rudder is linked to a radio control servo with a direct push-pull linkage, so that the rudder deflection angle can be directly controlled with the servo command.

Both the brushless motor and the rudder may be controlled either by using a radio link or by the onboard model control system, which is the

Table 3.1 Measured Parameters

Type of Test	ITTC Guideline	Measured Parameters	
Propulsion	7.5-02-03-01.1	Model speed	✓
		Resistance/External tow force	✓
		Propeller thrust and torque	✓
		Propeller rate of revolution	✓
		Model trim and sinkage	✓
Maneuverability (additional to Propulsion)	7.5-02-06-01	Time	✓
		Position	✓
		Heading	✓
		Yaw rate	✓
		Roll angle	✓
		Rudder angle	✓
		Force and moment on steering devices	x
		Model motions (6 d.o.f.)	✓
Seakeeping (additional to Maneuverability)	7.5-02-07-02.1	Model motion rates (6 d.o.f.)	✓
		Model accelerations (6 d.o.f.)	✓
		Impact pressures	x
		Water on deck	x
		Drift angle	x

default behavior. The user can choose between both control methods any time; there's always a human at the external transmitter to ensure maximum safety during tests.

3.2.1 Data Acquisition

In order to ensure that the model can be used for propulsion, maneuvering and seakeeping tests and is in accordance with the ITTC (International Towing Tank Conference) requirements, the following parameters have been measured (Table 3.1):

In order to obtain data for all the representative parameters, the following sensors have been installed onboard:

- Inertial Measurement Unit (IMU): having nine MEMS embedded sensors; including 3 axis accelerometers, 3 axis gyros and 3 axis magnetometers. The IMU has an internal processor that provides information on accelerations in the OX, OY and OZ axis, angular rates around these three axes and quaternion based orientation vectors (roll, pitch, yaw), both in RAW format and filtered by using Kalman techniques. This sensor

has been placed near the ship's center of gravity with the objective of improving its performance;

- Thrust sensor: a thrust gauge has been installed to measure the thrust generated by the propeller at the thrust bearing;
- Revolution and torque sensor: in order to measure the propeller revolutions and the torque generated by the engine, a torque and rpm sensor has been installed between both elements;
- Sonars: intended to measure the distance to the towing tank walls and feed an automatic heading control system;
- Not directly devoted to tested magnitudes, there are also a temperature sensor, battery voltage sensors and current sensors.

Data acquisition is achieved through an onboard mounted PC, placed forward on the bottom of the model. The software in charge of the data acquisition and processing and ship control is written in Microsoft .Net, and installed in this PC. This software is described in the following section. There is a Wi-Fi antenna at the ship's bow, connected to the onboard PC that enables a Wi-Fi link to an external, inshore workstation. This workstation is used to monitor the ship operation.

An overview of the model where its main components are shown is included in Figure 3.1.

3.2.2 Software Systems

In this section, the software designed and implemented to control the ship is described. Regarding the operational part of the developed software, there are three main tasks that have to be performed in real time in order to monitor

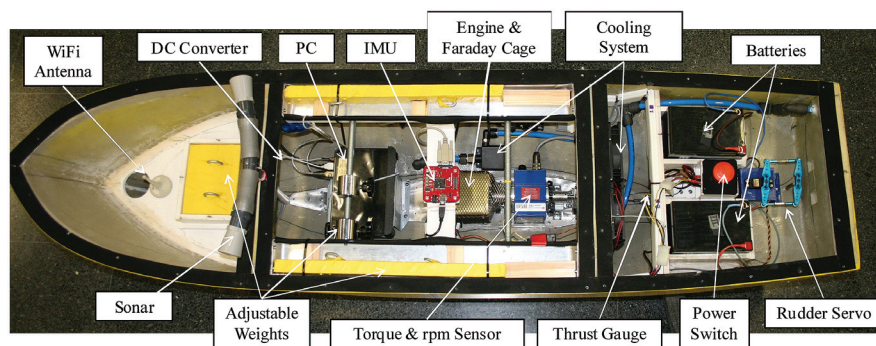


Figure 3.1 Ship scale model overview.

and control the ship: acquisition, computation and actuation. In every time step, once the system is working, all the sensor measurements are collected. The indispensable sensors that need to be connected to the system are: the Inertial Measurement Unit (IMU) which provides the acceleration, magnetic, angular rate and attitude measurements, the sonars and thrust gauge, in this case connected to a data acquisition board, and the revolution and torque sensor (Figure 3.2).

Once the sensor data are acquired, the system computes the proper signals to modify the rudder servo and the motor ESC commands. These signals can be set manually (using the software interface from the Wi-Fi linked workstation, or the external RC transmitter) or automatically. Applying a controller over the rudder servo, using the information from the sonar signals, it is possible to keep the model centered and in course along the towing tank. Another controller algorithm is used to control the ship speed.

The software is based on VB. NET and to interact with the system from an external workstation, a simple graphical user interface has been implemented (Figure 3.3).

From an external workstation, the user can start and finish the test, activate the sensors to measure, monitor the data sensors in real time, control the rudder servo and the motor manually using a slider or stop the motor and finish the test. All the acquired data measurements are saved in a file for a future analysis of the test.

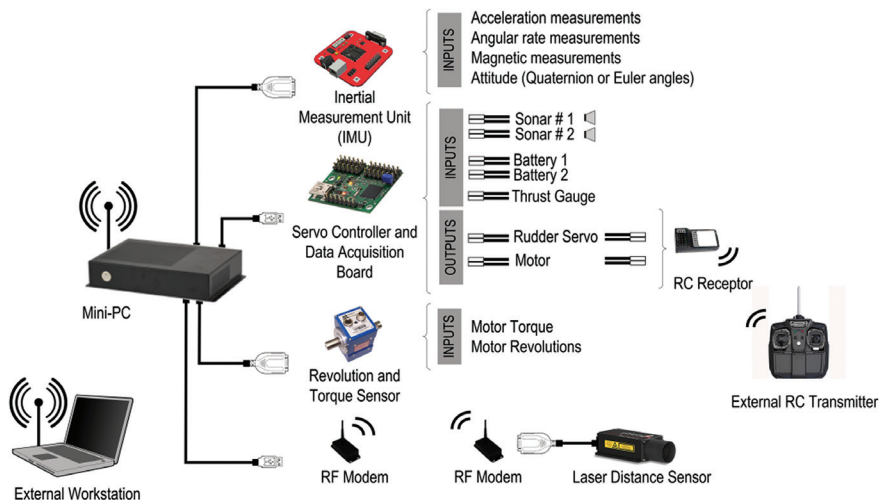


Figure 3.2 Connectivity between Mini-PC and sensors onboard.

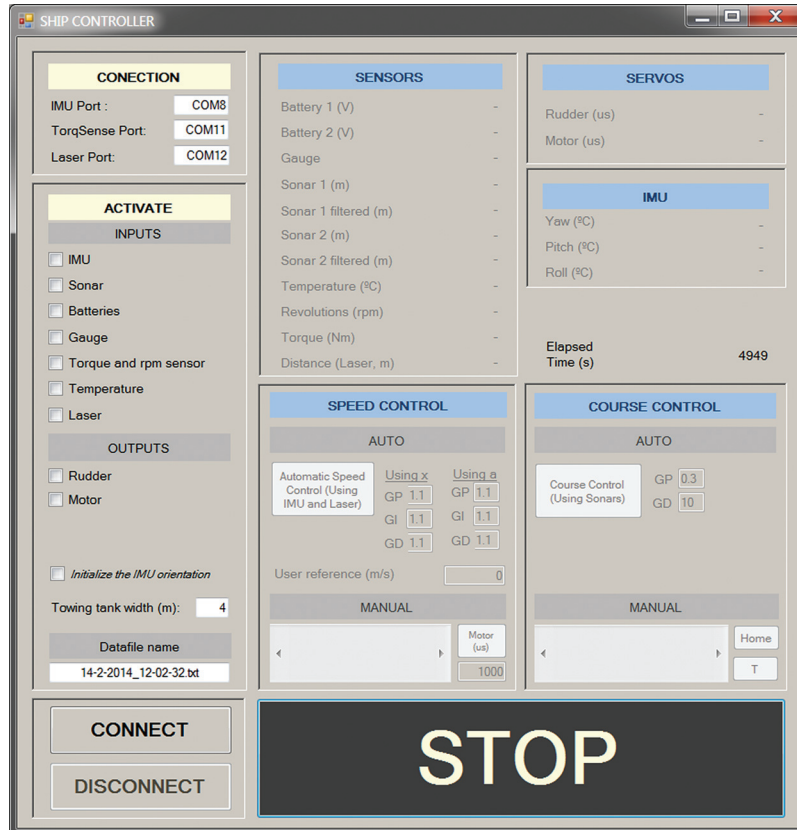


Figure 3.3 Graphical user interface to monitor/control the model from an external workstation.

3.2.3 Speed Control

The speed control of the model is done by setting an rpm command, which keeps engine revolutions constant by using a dedicated controller programmed in the governing software. Alternatively, a servo command may be used for setting a constant power input for the engine. In calm waters and for a given configuration of the ship model, there is a relationship between ship speed and propeller revolutions. By performing some preliminary tests at different speeds, this relation can be adjusted and used thereafter for testing within a simple, open loop controller. However, in case of testing with waves, these waves introduce an additional and strong drag component on the ship forward movement, and there is no practical way of establishing a similar sort of

relationship. For these cases, the towing carriage is used as a reference and the speed is maintained by keeping the ship model in a steady relative position to the carriage.

The speed control strategy to cope with this composed speed was initially tested as shown in Figure 3.4. It was initially done by means of a double PID controller; the upper section of the controller tries to match the ship speed with a set point selected by the user, c_v . This portion of the controller uses the derivative of the ship position along the tank, x , as an estimation of the ship speed, e_{vx} . The position x is measured through the Laser Range Finder sensor placed at the beginning of the towing tank, facing the ship poop, to capture the ship position along the tank, and send this information through a dedicated RF modem pair, to the Mini-PC onboard. The bottom section, on the other hand, uses the integral of the ship acceleration in its local x -axis from the onboard IMU, v_a , as an estimation of the ship speed, e_{va} . Each branch has its own PID controller, and the sum of both outputs is used to command the motor.

Both speed estimations come from different sensors, in different coordinate systems, with different noise perturbations and, over all, they have different natures. The estimation based on the derivative of the position along the tank has little or zero drift over time, and its mean value matches the real speed on the tank x axis, and changes slowly. On the other hand, the estimation based on the acceleration along the ship's local x -axis is computed by the onboard IMU, from its MEMS sensors, and is prone to severe noises, drift over time and changes quickly. Furthermore, the former estimation catches the slow

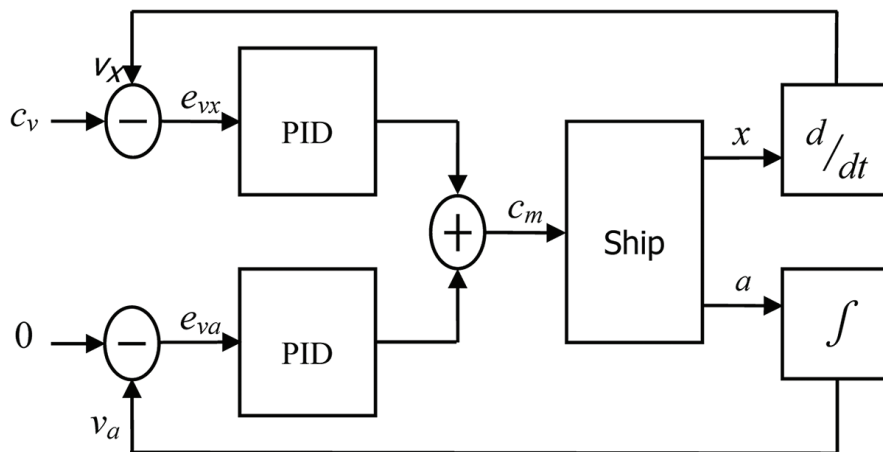


Figure 3.4 Double PID Speed control.

behavior of the ship speed, and the latter its quick changes. This is the reason to use different PID controllers with both estimations. The resulting controller follows the user-selected speed setpoint, with the upper branch eliminating any steady-state speed error, while minimizing quick speed changes with the lower branch.

Later on, a different speed control approach was introduced in order to improve its performance. Being the Laser Range Finder output an absolute measure of ship position, the speed obtained from its derivative is significantly more robust than the one estimated from the IMU in the first control scheme, and has no drift over time or with temperature. The new speed control algorithm is based in a complementary filter [6]. This filter estimates the ship speed from two different speed estimations, with different and complementary frequency components, as shown in Figure 3.5.

This two signal complementary filtering is based upon the use and availability of two independent noisy measurements of the ship speed, $v(s)$: the one from the derivative of the range finder position estimation ($v(s)+n_1(s)$) and the one from the integration of IMU acceleration ($v(s)+n_2(s)$). Each of these signals has their own spectral characteristics, here modeled by their different noise levels, $n_1(s)$ and $n_2(s)$. If both signals have complementary spectral characteristics, transfer functions may be chosen in such a way as to minimize speed estimation error. The general requirement is that one of the transfer functions complement the other. Thus, for both measurements of the speed signal [7]:

$$H_1(s) + H_2(s) = 1.$$

This will allow the signal component to pass through the system undistorted since the output of the system will always sum to one. In this case, n_1 is predominantly high-frequency noise and n_2 is low-frequency noise; these two

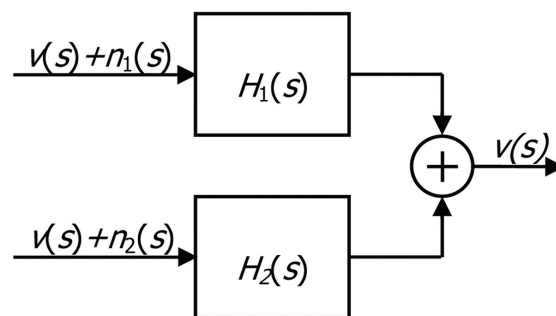


Figure 3.5 Speed control. complementary filter.

noise sources have complementary spectral characteristics. Choosing $H_1(s)$ to be a low-pass filter, and $H_2(s)$ a high-pass filter, both with the same, suitably cut frequency, the output v will not suffer from any delay in dynamic response due to low-pass filtering, and will be free of both high- and low-frequency noise.

3.2.4 Track-Keeping Control

Regarding heading control, IMU and sonar data are used for keeping the model centered and in course along the towing tank. In case these values are not accurate enough, heading control may be switched to a manual mode and an external RC transmitter could be used for course keeping. At first, the signals of the sonars to maintain the model centered on the tank and a Kalman filter taken data from the IMU were used to keep the course, the magnetometers' signals being of primary importance in this Kalman filter.

During testing, this arrangement showed to be not very effective because the steel rails of the carriage, placed all along at both sides of the tank, induced a shift in the magnetometer signals when the ship model was not perfectly centered at the tank. In addition, the magnetometers were also sensible to the electrical power lines coming across the tank. For these reasons only the sonar signals were used to keep both course and position, with the help of the relative position to the carriage, which have been used to keep the speed constant anyway.

3.2.5 Other Components

The power for all the elements is provided by two 12 V D.C batteries, placed abaft in the ship, providing room in their locations for longitudinal and transverse mass adjustment. These batteries have enough capacity for a whole day of operation.

The main propulsion system block, consisting of the already mentioned brushless motor (1), electronic speed control (ESC, not in view), two-stage planetary gearbox (2), rotational speed and torque sensor (3), elastic couplings (4), and an output shaft with Kardan couplings (5), is represented in Figure 3.6. The disposition of these elements in a single block allows a modular implementation of the whole system and simplifies the operations needed to install and uninstall it from a given ship model.

Finally, two adjustable weights have been placed in both sides of the ship model, and another one has been placed forward in the centerline. In both

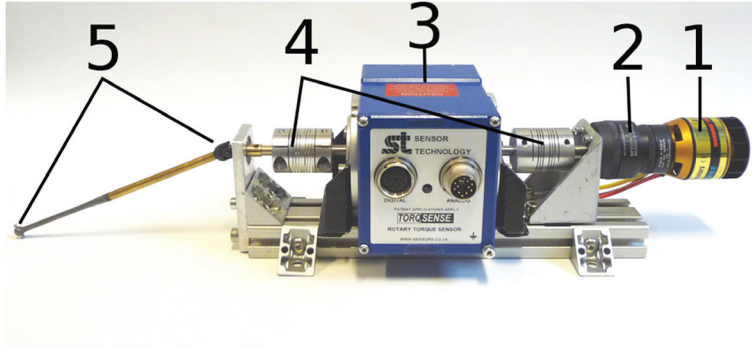


Figure 3.6 Propulsion system block.

cases, enough room has been left as to allow transversal and vertical mass adjustment. Moreover, two sliders with 0.5 kg weights have been installed for fine tuning of the mass distribution.

3.3 Testing

As mentioned above, the proposed model is mainly intended to be used in seakeeping tests in towing tanks, where the carriage may interfere in the motion of the ship. The application of the proposed model to one of these tests, aimed at predicting and preventing the appearance of parametric roll resonance, will be presented in this section.

As it has been already described, parametric roll resonance could generate large roll motions and lead to fatal consequences. The need for a detection system, and even for a guidance system, has been recursively stated by the maritime sector [8]. However, the main goal is to obtain systems that can, in a first stage, detect the appearance of parametric roll resonance, but that, in a second stage, can prevent it from developing.

As mentioned, there are some specific conditions that have to be present for parametric roll to appear, regarding both ship and waves characteristics. Wave encounter frequency should be around twice the ship natural roll frequency, their amplitude should be over a certain threshold that depends on ship characteristics, and their wavelength should be near the ship's length. Ship roll damping should be small enough not to dissipate all the energy that is generated by the parametric excitation. And finally, ship restoring arm variations due to wave passing along the hull, should be large enough as to counteract the effect of roll damping.

If parametric roll resonance wants to be prevented, it is obvious that there are three main approaches that could be used, and that consist in avoiding the presence of at least one of the aforementioned conditions.

The first alternative consists in acting on the ship damping components, or using stabilizing forces that oppose the heeling arms generated during the resonance process. The second alternative, aimed at reducing the amplitude of restoring arm variations, necessarily implies introducing modifications in hull forms. Finally, the third alternative is focused on avoiding wave encounter frequency being twice the ship natural roll frequency. If we consider a ship sailing at a given loading condition (and so with a constant natural roll frequency) in a specific seaway (frequency and amplitude), the only way of acting on the frequency ratio is by modifying encounter frequency. So, this alternative would be based on ship speed and heading variations that take the vessel out of the risk area defined by $\frac{\omega_e}{\omega_n} = 2$. This last approach is the one adopted in this work.

3.3.1 Prediction System

Regarding the prediction system, Artificial Neural Networks (ANN) have been used as a roll motion forecaster, exploiting their capabilities as nonlinear time series estimators, in order to subsequently detect any parametric roll event through the analysis of the forecasted time series [9]. In particular, multilayer perceptron neural networks (MPNNs) have been the structures selected to predict ship roll motion in different situations. The base neural network architecture used in this work is a multilayer perceptron network with two hidden layers, 30 neurons per layer, and one output layer. This initial structure is modified by increasing the number of neurons per layer, or the number of layers, in order to compare the prediction performance of different architectures and according to the complexity of the cases under analysis.

The network is fed with time series of roll motion, which are 20 seconds long and sampled at a frequency $F_s = 2$ Hz; hence the input vector \mathbf{x}^0 has 40 components. The network has only one output, which is the one step-ahead prediction. By substituting part of the input vector with the network output values, and recursively executing the system, longer predictions can be obtained from the initial 20 seconds. However, as the number of iterations grows, the prediction performance deteriorates accordingly.

The length of the roll time series has been selected taking into account two factors. On the one hand, the natural roll periods of the vessels chosen for the testing. In the loading conditions considered for these tests, this value is

7.48 seconds. On the other hand, parametric roll fully develops in a short period of time, usually no more than four rolling cycles [10].

The training of the artificial neural network forecaster has been achieved by using the roll time series obtained in the towing tank tests that will be described in the following section.

These algorithms have been implemented within the ship onboard control system, and their performance analyzed in some of the aforementioned towing tank tests.

3.3.2 Prevention System

Once parametric resonance has been detected, the control system should act modifying the model speed or heading in order to prevent the development of the phenomenon. In order to do so, the concept of stability diagrams has been applied. These diagrams display the areas in which, for a given loading condition and as a function of wave height and encounter frequency – natural roll frequency ratio and for different forward speeds, parametric roll takes place. From the analysis of these regions, the risk state of the ship at every moment could be determined and its speed and heading modified accordingly to take the model out of the risk area.

In order to set up these stability diagrams, a mathematical model of the ship behavior has been developed, validated, and implemented within the ship control system in order to compute the stability areas for the different loading conditions tested.

This model is a one degree of freedom nonlinear model of the ship roll motion:

$$(I_{xx} + A_{44}) \cdot \ddot{\phi} + B_{44, T} \cdot \dot{\phi} + C_{44}(\phi, t) = 0,$$

where I_{xx} and A_{44} are respectively the mass and added mass moments of inertia in roll, $B_{44, T}$ represents the nonlinear damping term and $C_{44}(\phi, t)$ is the time varying nonlinear restoring coefficient. In this case, the moment and the added moment of inertia have been obtained by measuring the natural roll frequency from a zero speed roll decay test, carried out with the developed ship scale model.

While trying to model parametric roll resonance, it has been seen that both heave and pitch motions have a clear influence in the appearance of the phenomenon, together with the effects of the wave moving along the hull. So, including the influence of these factors is of paramount importance for a good performance of the mathematical model. In this work, the influence of these factors has been taken into account while computing the restoring term,

by adopting the quasi-static “look up table” approach, described by [11] and required by the ABS Guidelines [12] for modelling the variation of the ship restoring capabilities in longitudinal waves.

Moreover, and regarding the roll damping, it has been shown that it is essential for a good simulation of large amplitude roll motion, to consider this parameter as highly nonlinear. In order to account for this fact, roll damping has been decomposed into two terms, one linear component, which is supposed to be dominant at small roll angles, and a quadratic one, which is necessary to model the effects of damping at large roll angles. This approach has also been applied by many authors for modelling parametric roll, that is, [13], with accurate results. In order to determine the two damping coefficients ($B_{44, a}$, $B_{44, b}$) in the most accurate way, roll decay tests for different forward speeds have been carried out in still water for the loading condition under analysis. The procedure followed for determining the damping coefficients from these tests is that described in [14].

Once the model was correctly set up and validated, it was executed for different combinations of wave height and frequency, the maximum roll amplitude for these time series was computed and the stability diagrams developed.

3.3.3 Towing Tank Tests and Results

The proposed system has been used to perform different tests, some of which have been published elsewhere [15]. The main objective of these tests was to analyze, predict and prevent the phenomenon of parametric roll resonance. It is in this sort of tests, characterized by large amplitude oscillations in both roll and pitch motions, where the proposed system performs best as it can take information on board without disturbing the free motion of the ship model.

To illustrate the influence of the towing device on the measures obtained in this kind of tests, Figure 3.7 is presented. On it, the pitch and roll motions of a conventional carriage-towed model (Figure 3.8) in a similar parametric rolling test, are included.

As it can be observed, the ship pitch motion presents a series of peaks (the most relevant in seconds 140, 180, 220 and 300), which are due to the interference of the towing device. These interferences not only influence the model pitch motion, but could also affect the development of parametric roll and so, the reliability of the test.

The tests campaign has been carried out in the towing tank of the Escuela Técnica Superior de Ingenieros Navales of the Technical University of Madrid.

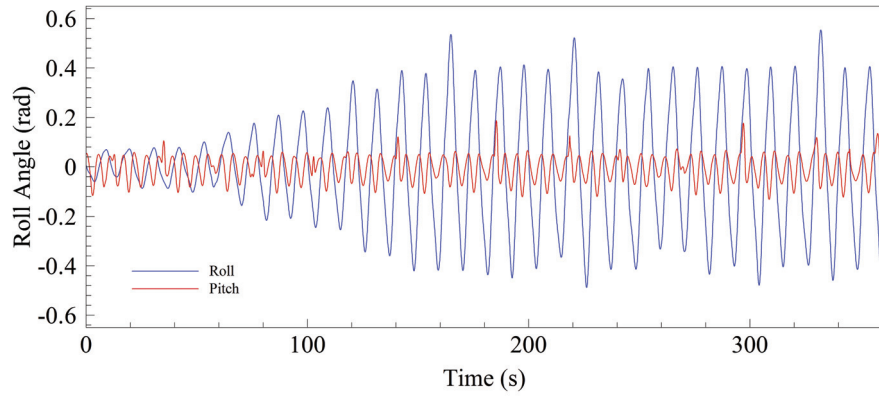


Figure 3.7 Roll and pitch motions in parametric roll resonance. Conventional carriage-towed model.

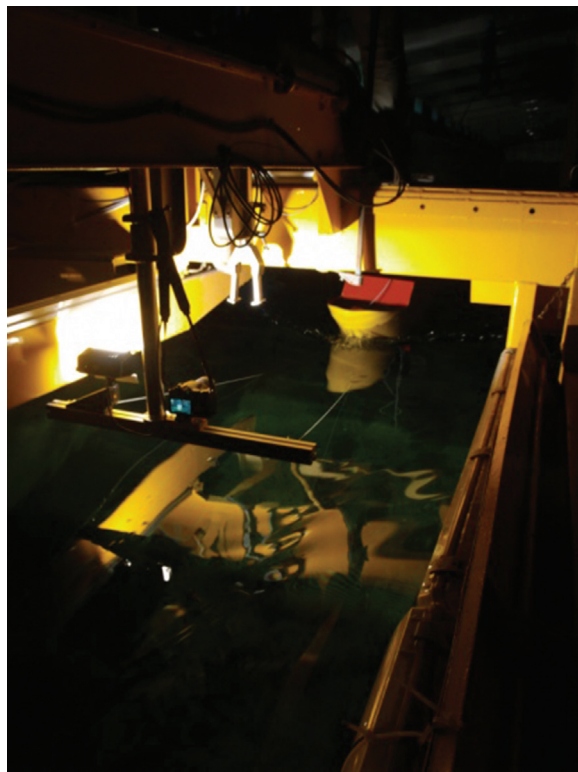


Figure 3.8 Conventional carriage-towed model during testing.

This tank is 100 meters long, 3.8 meters wide and 2.2 meters deep. It is equipped with a screen type wave generator, directed by a wave generation software, capable of generating longitudinal regular and irregular waves according to a broad set of parameters and spectra. The basin is also equipped with a towing carriage able to develop a speed of up to 4.5 m/s. As it has already been mentioned, in this test campaign, trials at different forward speeds and also at zero speed have been carried out.

Regarding the zero speed runs, in order to keep the model in position and to try to avoid as much as possible any interferences of the restraining devices in the ship motions, two fixing ropes with two springs have been tightened to the sides of the basin and to a rotary element fixed to the model bow. Moreover, another restraining rope has been fitted between the stern of the model and the towing carriage, stowed just behind of it. However, this last rope has been kept loose and partially immersed, being enough for keeping the model head to seas without producing a major influence on its motion. In the forward speed test runs, the model has been left sailing completely free, with the exception of a security rope that would be used just in case the control of the ship was lost.

In order to set the adequate speed for each test run, a previous calibration for different wave conditions has been carried out to establish the needed engine output power (engine servo command) for reaching the desired speed as a function of wave height and frequency. The exact speed value developed in each of the test runs has been measured by following the model with the towing carriage, which has provided the instantaneous speed along the run. The calibration curve has been updated as the different runs were completed, providing more information for subsequent tests. However and considering that the model is free to move in the six degrees of freedom, the instantaneous speed of the model may be affected by surge motion, especially at the conditions with highest waves.

A total number of 105 test runs have been carried out in head regular waves. Different combinations of wave height (ranging from 0.255 m to 1.245 m model scale) and ratio between encounter frequency and natural roll frequency (from 1.80 to 2.30) have been considered for three different values of forward speed (Froude numbers 0.1, 0.15 and 0.2) and zero speed, and two different values of metacentric height (0.370 m and 0.436 m). From the whole set of test runs, 55 correspond to the 0.370 m GM case, while 50 correspond to a GM of 0.436 m.

The results obtained from the different test runs have been applied for determining ship roll damping coefficients and validating the performance of the mathematical model described in the previous subsection, for validating



Figure 3.9 Proposed model during testing.

the correctness of the so computed stability diagrams, and for training and testing the ANN detection system.

In addition to this, the results of pitch and roll motion obtained with the proposed model are presented in Figure 3.10, for the sake of comparison with the results obtained with the conventional model (Figure 3.7). As it can be seen, the pitch time series doesn't present the peaks observed in the conventional

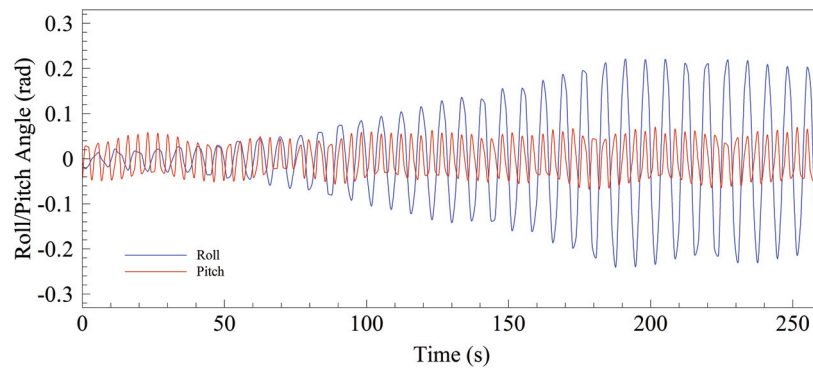


Figure 3.10 Roll and pitch motions in parametric roll resonance. Proposed model.

model measurements, as no interference between model and carriage occurs in this case.

3.3.3.1 Mathematical model validation

As a first step, the results obtained from the towing tank tests have been used for validating the performance of the roll motion nonlinear mathematical model to predict the amplitude of the resulting roll motion.

In most cases, the results obtained from the model are quite accurate, and correctly simulate the roll motion of the ship both in resonant and non-resonant conditions.

Examples for both situations could be seen in Figures 3.11 and 3.12:

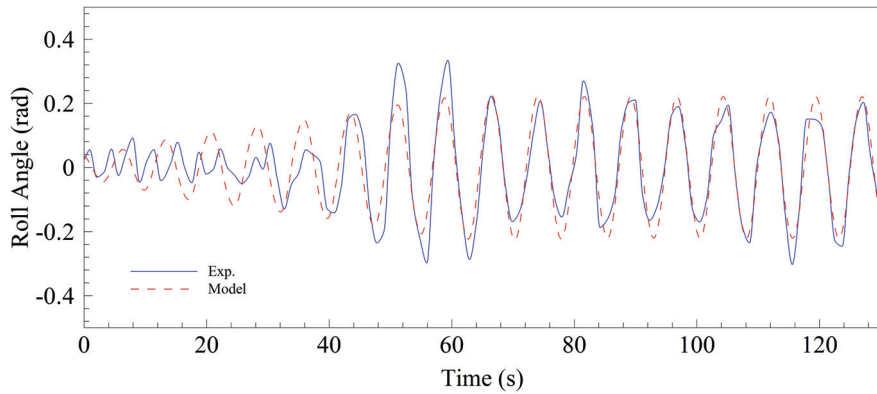


Figure 3.11 Comparison between experimental and numerical data. Resonant case.

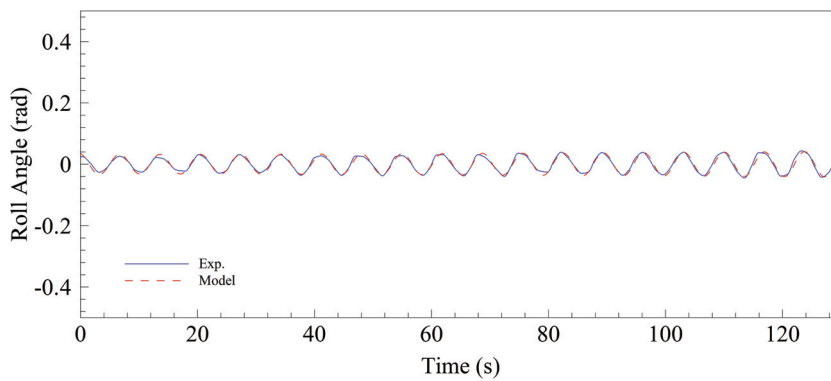


Figure 3.12 Comparison between experimental and numerical data. Non-Resonant case.

3.3.3.2 Validation of stability diagrams

Once the model has been validated, it has been recursively executed for a set of combinations of different wave frequencies and heights, covering the frequency ratio range from 1.70 to 2.40 and wave heights from 0.20 to 1.20 m, at each operational condition under consideration (four speeds), in order to set up the stability diagrams. Once computed, the results have been compared to those obtained in the towing tank tests. To illustrate this comparison, the results obtained from these experiments (Figure 3.13) have been superimposed on the corresponding mathematical plots (Figure 3.14); light dots represent non-resonant conditions, while resonance is shown by the dark dots.

As can be seen in Figure 3.14, the shape of the unstable region matches the results obtained in the towing tank tests, that together with the accurate results obtained while computing roll amplitude, show a good performance of the mathematical model.

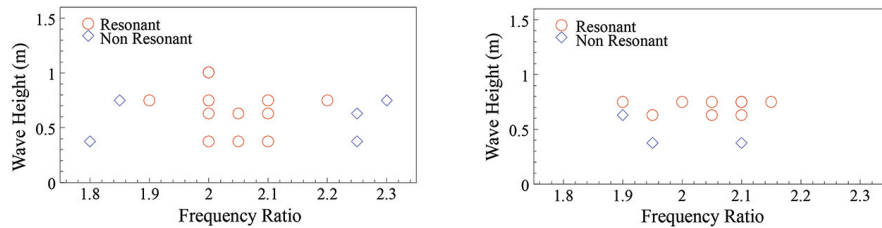


Figure 3.13 Experimental stability diagrams. $F_n = 0.1$. (Left), $F_n = 0.15$ (Right), $GM = 0.370$ m.

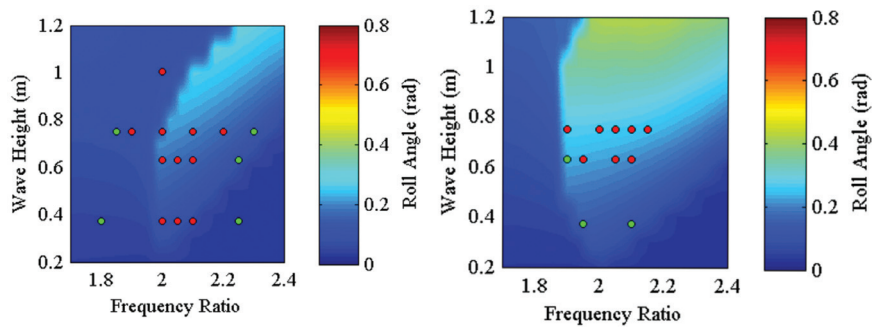


Figure 3.14 Comparison between experimental and numerical stability diagrams. $F_n = 0.1$. (Left), $F_n = 0.15$ (Right), $GM = 0.370$ m.

3.3.3.3 Prediction system tests

To forecast the onset and development of the parametric roll phenomena, some standard perceptron ANNs have been used. Several ANN architectures were tested and the overall best results were obtained with 3 layers of 30 neurons each.

The training cases for the ANNs have been obtained from the experiments that have been carried out with different values of wave frequency and amplitude at a Froude number of 0.2, consisting of 14 time series averaging a full scale length of 420 seconds. IMU output data was sampled by the on-board computer at a rate of 50 data sets per second. As for this particular ship model, the roll period of oscillation is of several seconds, the data used for training the ANNs was under-sampled to 2 Hz, which was more than enough to capture the events and permit reducing the size of the data set used. This resulted in a total number of 11169 training cases.

Encounter frequency – natural roll frequency ratio ranged from 1.8 to 2.3, implying that there would be cases where parametric roll was not present. Due to this fact, the performance of the system in a condition where only small roll amplitudes appear due to small transversal excitations or when roll motions decrease (cases that were not present in the mathematical model tests as no other excitation was present apart from head waves) could be evaluated.

The tests have been performed on both regular and irregular waves in cases ranging from small to heavy parametric roll. In regular waves, the RMS error when predicting 10 seconds ahead has been of the order of 10^{-3} in cases presenting large roll amplitudes and it reduces to 10^{-4} in cases with small amplitudes.

Two examples of these predictions are shown in Figures 3.15 and 3.16, which include one case with fully developed parametric roll, and another one without any resonant motions. On these figures, the ANN forecast is represented by the dotted line, while the real data is represented by full lines. Figure 3.15 is a typical example of a case presenting large amplitudes, while in Figure 3.16 no resonance motion takes place. As can be observed in both cases, the results are very good.

Further details of the characteristics and performance of the forecasting ANN system have been presented by the authors in [16]. There, the forecasting system has been implemented on a ship model instrumented with accelerometers and tested by using standard towing tank methods. The data used for the Figure 3.7 plot has been obtained during this testing campaign.

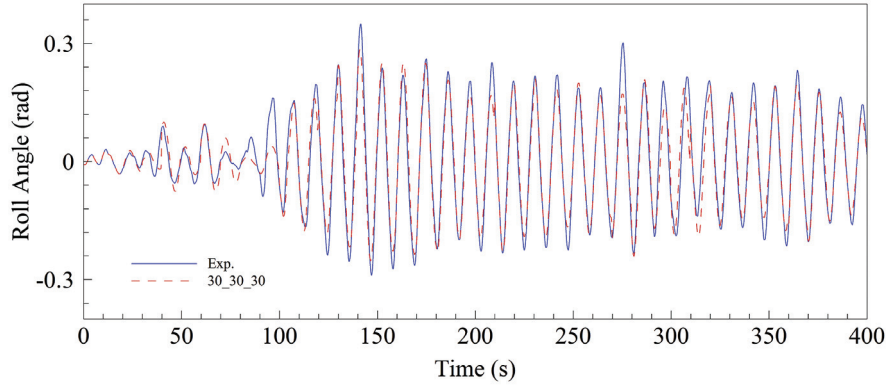


Figure 3.15 Forecast results. 30 neuron, 3 layer MP. 10 seconds prediction. Resonant case.

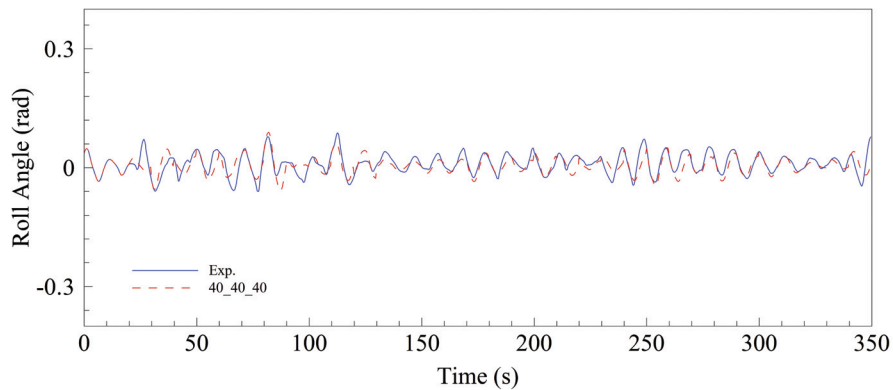


Figure 3.16 Forecast results. 30 neuron, 3 layer mp. 10 Seconds prediction. Non Resonant case.

3.4 Conclusions and Future Work

The development and implementation of an autonomous scale ship model for towing tank testing has been presented as well as some of the results obtained with it during a real towing tank test campaign. The system is aimed to be installed on board of self-propelled models, acting as an autopilot that controls speed and track, the latter by maintaining course and keeping the model centered in the tank. It also has an IMU with a 3-axis accelerometer, a gyroscope and a magnetometer and, in addition, it measures the torque, rotational speed and propulsive force at the propeller. A model ship so

instrumented is able to move without any restriction along any of its six degrees of motion; consequently, the system produces optimal measurements even in tests cases presenting motions of large amplitude.

At its present development stage, the system only needs to use the towing carriage as a reference for speed and position. A more advanced version that could eliminate the use of this carriage is under development. This towing carriage, together with its rails, propulsion and instrumentation, is a very costly piece of hardware. The final version of the system could be constructed at a fraction of this cost and it will be a true towless towing tank, as it will allow performing any standard towing tank test without the need of an actual tow.

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