Experimental Parametric Roll Resonance Characterization of a Stern Trawler in Head Seas

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ABSTRACT

Parametric roll resonance is a well known phenomenon that, under certain conditions, induces very large amplitude roll motions that could lead to consequences ranging from simple minor issues to even catastrophic ones. The need for a parametric roll real time prediction system has been stated by the industry in the last years. This work describes the results of the scale model experiments of a stern trawler under parametric roll conditions; the objective of these tests is to characterize its dynamical behaviour in these situations, and to test in realistic conditions the roll motion forecasting system developed by the authors. Moreover, the results of these forecasts for some test cases are also presented in this work.

Keywords: *parametric roll, fishing vessels, model tests*

1. INTRODUCTION

Parametric roll resonance is a well known and broadly studied phenomenon for the maritime community. Under a set of given conditions, including a wave encounter frequency of approximately twice the ship's natural roll frequency, a wavelength almost equal to the ship length and a wave amplitude larger than a ship dependent threshold, the roll motion of a ship sailing in head or stern seas and affected by roll resonance could quickly increase, reaching very large roll angles with apparently no transversal excitation that generates those motions.

Parametric rolling is caused by the periodic variations of stability levels due to wave passing along the hull and is more severe in those ships where those variations are larger, such us containerships, Ro-Ro vessels, cruise ships or fishing vessels (due to large bow flares or hanging sterns). The consequences of such an event could range from simple minor issues, to catastrophic cargo damage, crew or passenger injuries or even ship capsizing.

This fact has empowered the industry and the research community to develop different strategies to prevent parametric roll resonance from appearing (France et al., 2001, Dohlie, 2006, IMO, 2007).

The first step in this direction was the development of guidelines to the masters to avoid those situations in which resonance was more likely to develop. These guidelines are mainly based on the observation of the prevailing sea conditions and ship sailing characteristics, and the use of polar diagrams to determine if the ship is on a risky area (IMO, 2004).

This manual methodology has been followed by the development of specific software (Amarcon Octopus[1], SeaWare enRoute[2]), that based on the same principles of combined analysis of weather forecast reports and ship sailing parameters, including heading and speed, define resonance risk areas in a medium time horizon (15 to 30 minutes). A detailed review of this topic can be found in (Themelis and Spyrou, 2007).

Finally, in the last five years, a third approach has started being developed. The main characteristic of these systems is the capability to detect the appearance of parametric rolling in the short term, alerting the crew and allowing them to take immediate corrective measures. Some of these alternatives are those of Holden et al. (2007), McCue and Bulian (2007), Galeazzi et al. (2010) or that proposed by the authors of this work (Míguez et al, 2010,2011), based on the application of neural networks.

The main objective of the algorithms described in these last two references, is to be integrated in a parametric roll advance warning and detection system, that will be based on a two step alarm approach. A first warning should be displayed to the crew based on the analysis of the sailing conditions, following the approach of the guidance software mentioned above and that will alert the crew about the possible risk of roll resonance. The second warning should be generated by the short term detection schemes, and will alert from the near development of the phenomenon.

The present work has two main objectives. On one hand, studying the dynamic behaviour of the vessel in parametric rolling conditions; this information will be of paramount importance for determining under which sailing parameters the ship is in risk of resonance, and so for the display of the aforementioned first step alarm.

[1] www.amarcon.com
[2] www.amiwx.com

On the other hand, the short term detection algorithms developed by the authors have been, by now, tested against a mathematical model of three degrees of freedom in head regular waves (Míguez et al., 2010). However, it is also necessary to study their performance under more realistic conditions, such us irregular waves. This analysis has also been carried out in this work.

In order to cover these two main objectives, an extensive towing tank test campaign has been accomplished in the Towing Tank of the ETSIN (Technical University of Madrid).

A scale model of a medium sized trawler with high tendency to developing parametric roll has been used and test runs at different speeds and longitudinal wave types (both regular and irregular), leading to resonant and non resonant behaviours, have been done.

In this work, the results of some of the aforementioned tests are presented, together with the conclusions obtained after their study, aimed at characterizing the phenomenon of parametric rolling for the selected ship.

Furthermore, the roll motion time series obtained with the parametric roll prediction system for some of the test runs will be presented, analyzing the performance of the system in a quite realistic scenario

2. MODEL TESTS

2.1 Stern Trawler Model

The ship analyzed in this work is a medium sized stern trawler, with an acute tendency towards developing parametric roll resonance in not very heavy seas, in part due to its transom stern hull forms. This ship has also been studied by de Juana Gamo et al. (2005) and its main characteristics are described in Table 1. A 1/18.75th scale model has been used for the towing tank experiments.

Table 1: Test vessel main characteristics

Overall Length	34.50 m
Breadth	8.00 m
Depth	3.65 m
Displacement	450.0 t
Metacentric Height	0.35 m
Natural Roll Frequency	0.563 rad/s

2.2 Experimental Arrangement

The aforementioned scale model tests have been carried out in the test basin of the Escuela Técnica Superior de Ingenieros Navales of the Technical University of Madrid. This towing 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 an AwaSys[3] 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.

The scale model is a wooden one with adjustable weights. Roll and pitch angles together with roll and pitch accelerations have been measured at a 50 Hz frequency through three onboard mounted accelerometers. Wave elevation has also been measured, using a carriage mounted wave probe.

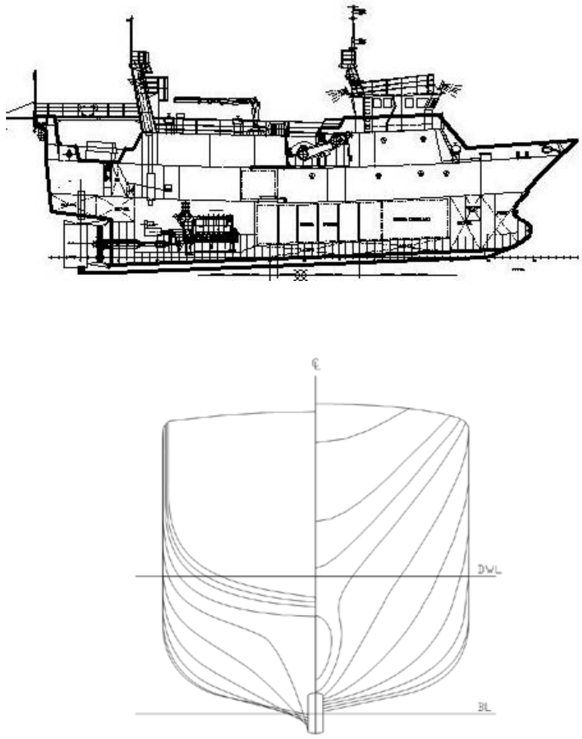


Figure 1 Selected stern trawler arrangement and hull forms

Taking in account that the surge, sway and yaw influence in the development of parametric roll resonance may be neglected compared to that of heave, roll and pitch (Neves and Rodriguez, 2006), the model restraining devices were fitted to try to limit the first three motions to the minimum possible. These restraining devices consisted in two ropes fixed to an articulation in the bow, while another one was fitted at the same level to the transom.

While carrying out the zero speed experiments, the forward ropes were fastened to the sides of the basin, forming an isosceles triangle, while the stern one was fastened to the towing carriage, situated immediately after the model. In the case of the forward speed experiments, bow ropes were fastened to the carriage, while the stern one was holding from a beam extending after the carriage from its rear part.

[3] http://www.hydrosoft.civil.aau.dk/AwaSys/

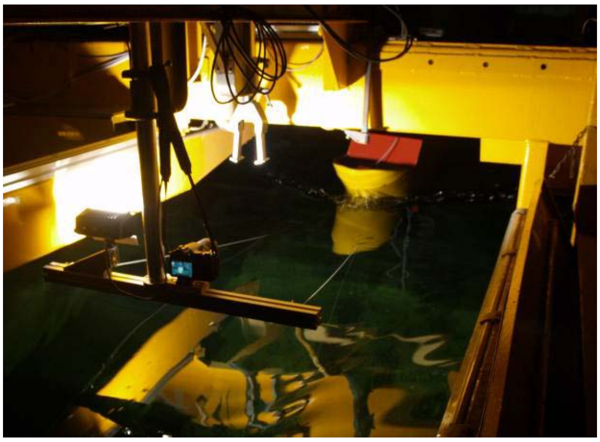


Figure 2 Model arrangement.

2.3 Test Cases

The main objective of the tests was to study the development of the parametric roll resonance phenomenon under different sailing situations, from the simplest to more realistic ones, including the analysis of the influence of forward speed and wave parameters on the intensity of the phenomenon.

The test campaign was divided in two. On one hand, the ship has been tested in longitudinal linear Airy waves, for different values of encounter frequency-natural roll frequency ratio, wave amplitude and forward speed. The main objective of this first part was to determine the influence of frequency ratios, forward speed and wave amplitude on the amplitude of rolling motions.

On the other hand, test in longitudinal irregular waves have also been carried out, for a given wave spectra, with the objective of determining how the spectrum parameters affect the development of parametric roll resonance.

Regular Waves. As has been previously described, the main parameter affecting the appearance or parametric roll resonance is the ratio between encounter frequency and natural roll frequency. The most critical value is around 2, but resonance is also likely for ratios between 1.9 and 2.2. Once this condition is satisfied, other parameters are also needed to trigger resonance. Wave amplitude should be over a given threshold and regarding wavelength, the more similar to ship length, the larger the developed roll motions will be.

The proposed test matrix includes, at four different forward speeds, test cases for combinations of frequency ratios between 1.7 and 2.3 and wave heights between 0.5 and 3 m; the complete test set is composed of 24 different combinations for the zero speed case, 16 for Froude numbers of 0.1 and 0.2 and 13 for the Froude 0.3 case.

One of the main objectives of this study was to determine the areas in which, as a function of wave height and encounter frequency – natural roll frequency ratio, and for different forward speeds, parametric rolling takes place (limits of stability). From the analysis of these regions, the risk state of the ship at every moment could be determined, making it possible to trigger the first step alarm described above.

Two examples of these limits of stability could be seen in Figures 3 and 4, for Froude numbers of 0 and 0.2 respectively, where resonant and non resonant combinations are shown.

As can be seen from those figures, reduced damping in the zero speed case implies that parametric roll develops at smaller wave heights than in the case with forward speed. Moreover, it can be appreciated that the non stable region tends to extend to the right in the Fn 0.2 case; this fact has been already described by Neves and Rodríguez (2007), and is due to the strong coupling between vertical motions (heave and pitch) and roll.

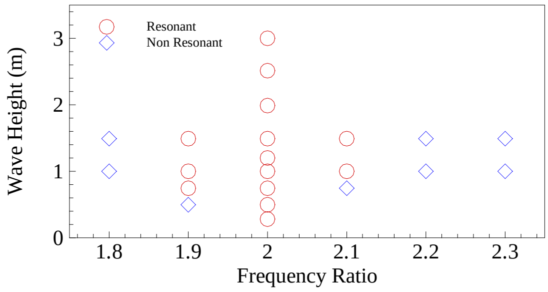


Figure 3 Stability limits. Fn = 0.

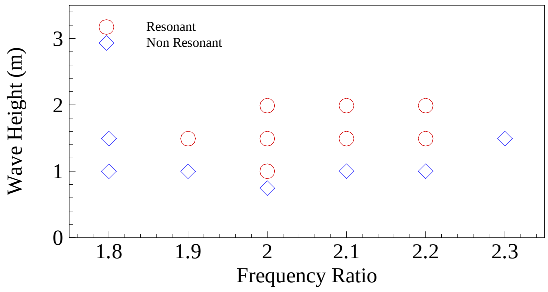


Figure 4 Stability limits. Fn = 0.2.

Regarding the influence of forward speed and wave height in the amplitude of the generated roll motions, from the observation of Figure 5, it can be concluded that an increase in wave height implies, in all cases, and increase in the amplitude of the steady state roll motion. Referring to forward speed, at the lowest wave heights, it has been observed that higher speeds imply lower angles, although the difference is not very significant at the smaller Froude numbers. However, at larger wave heights, it has been observed that the increase of speed could lead to an amplification of roll motion, as could be appreciated for the case of Fn 0.2 and a wave height of 2 m.

Figure 5 Roll angle as a function of wave height and Froude number. Frequency ratio = 2.

Irregular Waves. In the irregular wave case, experiments at four different forward speeds have also been carried out. TMA spectrum (Bouws et al., 1985) has been selected for wave generation. In order to study the influence of significant wave height, peak frequency and peak enhancement factor (PEF) on resonance development and amplitude, combinations of significant wave heights from 1 to 2.5 meters, encounter peak frequency – natural roll frequency ratios from 1.9 to 2.2 and peak enhancement factors of 3,5 and 7 have been considered.

Regarding the influence of wave height in the roll motion, the values of the average and maximum reached roll angles for tests at zero forward speed, peak frequency – natural roll frequency ratio of 2 and four different significant wave heights, are presented on Figure 6.

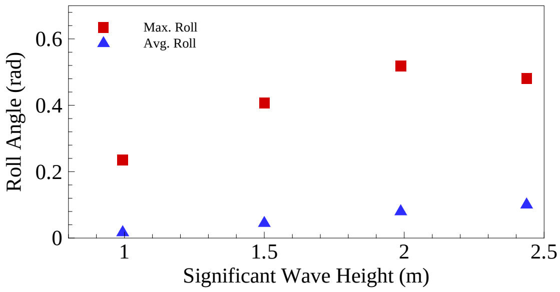
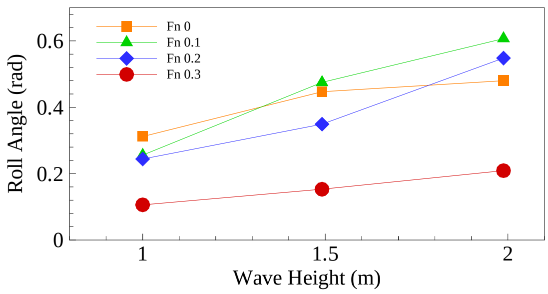


Figure 6 Significant wave height influence on roll motion. Fn = 0. Frequency ratio = 2. PEF =7.

From its analysis, it can be concluded that the effects of an increase in significant wave heigth in the irregular wave case, are the same as those observed in regular waves regarding roll motion, including the reduced amplification at the largest values of wave heigth for the maximum roll values. Moreover, it can be observed that maximum roll amplitudes are very similar to those of the regular wave case. These is due to the fact that those values are achieved during parametric roll events, caused by the most energetic waves in the vicinity of the peak spectrum and with a heigth similar to the significant one, which could be asimilated to a regular wave of that characteristics.



For studying the influence of frequency ratio and peak enhancement factor, the results obtained for the Froude 0.2 tests cases will be presented. These tests consist of a total of 34 runs carried out at encounter peak frequency – natural roll frequency ratios between 1.9 and 2.2, peak enhancement factors of 3.5 and 7 and a significant wave height of 1.5 meters. The results of the average mean and maximum roll angles for all the series with the same parameters combination are presented in Figure 7.

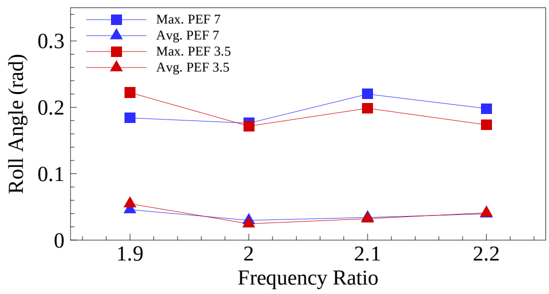


Figure 7 Frequency ratio and PEF influence on roll motion.

From the analysis of the aforementioned graph, and regarding the effects of the peak enhancement factor, it can be observed that higher PEF values imply higher maximum roll amplitudes, which coincide with resonance periods due to waves with frequencies near the spectrum peak. Considering the fact that higher PEF values mean more energetic waves in the near vicinity of the peak, the observed behaviour is clear. Moreover, the maximum roll values are found at the neighbour values to the resonant tuning ratio, i.e. 1.9 and 2.1, while amplitude decreases while moving further to the right (2.2 ratio).

3. PARAMETRIC ROLL FORECASTING

The analysis carried out in the previous section, was aimed at increasing the knowledge about the selected trawler dynamics in resonant conditions, in order to be able to determine its risk while sailing from the analysis of the present conditions and to trigger a first step alarm.

In order to detect the onset of parametric roll resonance in the short term, the authors have proposed the use of Artificial Neural Networks (ANNs) to forecast the ship roll motions, while the parametric roll detection should be done by analyzing these forecasted data.

ANNs are a type of mathematic algorithm with the property of adequately approximating any function, also nonlinear ones, if a good selection of its architecture is done (Cybenko, 1989) and after a process of training.

These algorithms have been broadly used in many fields; in ship motion analysis, some references of the use of ANNs could be Ebada an Abdel-Maksoud (2006) or Xing and McCue (2009).

Basically, ANNs are composed of an input layer, which receive the data, a series of hidden layers that contain the neurons, which process the data, and an output layer. In each neuron, the inputs are weighed, a bias is added and a summation of all the inputs is carried out. This summation is then processed by an activation function and the result is sent to the next neuron layer.

The training process consists in feeding the network with known data, including inputs and their corresponding outputs, and adjusting the weights and biases to minimize error between target and network result.

The selected architecture has 40 inputs (corresponding to 20 seconds of the roll time series) and 1 output (the 0.5 seconds ahead prediction). The forecasting process is done by feeding the network with those 40 inputs and recursively executing the system in order to obtain the desired forecast length.

In (Míguez González et al., 2010), the authors applied this methodology to forecast ship motions from a three degrees of freedom mathematical model in longitudinal regular waves, obtaining promising results. However, the need for investigating their performance in more realistic conditions was acknowledged.

3.1 Test Cases

In order to test the behavior of the proposed system in such a more realistic scenario, the data obtained from the towing tank tests, for a speed equivalent to a Froude number of 0.2 (7 knots of real ship speed), both in regular and irregular seas, have been used.

In the regular wave case, training and testing time series have been obtained from 16 experiments with different values of wave frequency and amplitude, with an average full scale length of 420 seconds. Encounter frequency – natural roll frequency ratio ranged from 1.8 to 2.3, implying that there were cases where parametric roll was not present. This fact allowed us to evaluate the performance of the system in a condition where only small roll amplitudes appeared due to external transversal excitations (cases that were not present in the mathematical model tests, as no other excitation was present apart from head waves).

The testing of the system has been done by using a time series corresponding to a frequency ratio of 2.0 and a wave amplitude of 0.745 m, in which parametric rolling is fully developed (Test 1).

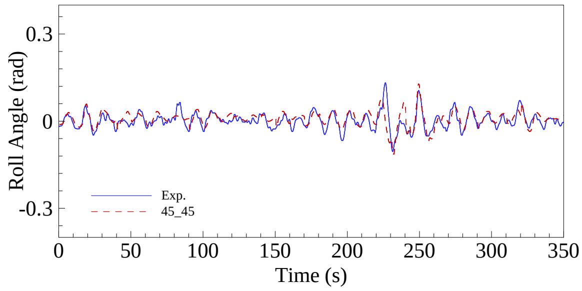
During the experiments, time series were sampled at a frequency of 50 Hz. For generating the ANN training and test cases, time series were resampled at 2 Hz and divided into 40+1 time steps, being the 40 inputs of the network and their corresponding output. 11169 training cases were obtained this way from the experimental data.

In the irregular wave case, the training and testing of the MPNN system has been done through the experiments corresponding to the TMA spectrum, peak shape parameter of 7 and significant wave height of 1.5 meters. The whole set of training cases has been obtained from 15 time series where roll resonance either takes place or not, with an average real scale length of about 380 seconds.

For testing the system, two time series have been selected, one corresponding to a frequency ratio of 2.1 in which resonance takes place (Test 2) and the other to 2.0 in which it doesn´t (Test 3).

Following the same methodology described for the regular waves, 10898 cases were obtained and used in the training process.

Taking into account that realistic data implies the need of a more complex model for obtaining good results, different network structures have been tested in both cases, modifying the number of hidden layers and neurons. The results obtained with the best performing structure for a forecast of 10 seconds ahead, will be presented in the next section.



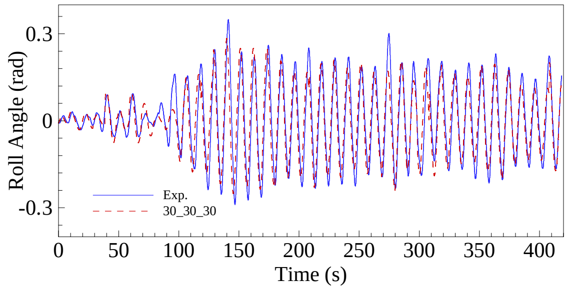
3.2 Results

Regarding the regular wave case, in Figure 8, the results obtained with the best performing MPNN (three layers and 30 neurons per layer), are included. The obtained error value (MSE) for the presented case is 12.04 $x10^{-4}$.

Reffering to the irregular wave case, in Figures 9 and 10, the selected test time series are presented.

Figure 8 Test 1. Forecast results. 30 neuron, 3 layer MP.

As can be seen, in Test 2 no parametric rolling events develop, being only present



small amplitude roll motions due to the natural roll motion of the ship and the effects of the present external disturbances (towing device, wall rebounds, etc.). The maximum roll amplitude reaches approximately 0.13 rad (7.4 degrees) around the second 225, and soon dissipates into the average of 1.2 degrees that could be found along the whole time series.

In test 3, no large roll motions appear until a slightly larger roll to port around second 215 and an adequate wave sequence, excite an episode of parametric rolling, that lasts for 6 rolling cycles (approximately from second 240 to 310) and that dissipates when wave conditions change. The error values (MSE) of these predictions are 5.60 $x10^{-4}$ for Test 2 and 6.66 $x10^{-4}$ for Test 3.

From the results and figures above, it can be concluded that the forecasts provided by the networks are very accurate in all test cases, precisely tracking the ship roll response.

In Test 1, the prediction precisely estimates steady state roll angle and the transient during resonance development, and also the peaks present around second 50.

Regarding the irregular waves, in Test 2 the system tracks the roll motion without overpredictions that could lead to misdetections.

Figure 9 Test 2. Forecast results. 45 neuron, 2 layer MP.

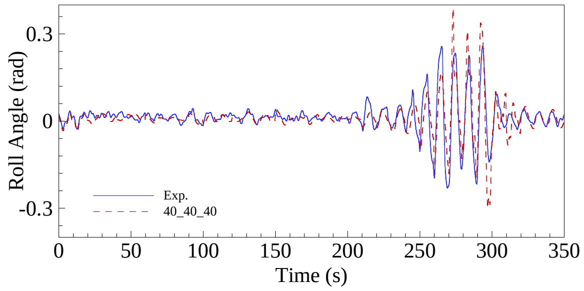


Figure 10 Test 3. Forecast results. 40 neuron, 3 layer MP.

In Test 3, the forecaster performs in the same way until resonance starts to develop around second 240, and tracks the increasing in roll motion until steady state is reached. Once in this point, some overestimation of roll amplitude could be appreciated.

4. CONCLUSIONS

This work presented part of the activities carried out by the authors for developing a parametric roll advance warning/detection system, that could prevent the crews of the vessel about the ship suffering an episode of parametric roll resonance and also alert them in the short term if the phenomenon is developing.

In this occasion, two main objectives were followed: on one hand, the study of ship behaviour in realistic conditions under parametric resonance; on the other, the testing of a neural networks based roll motion forecasting system in such conditions.

This was done by carrying out towing tank tests of a stern trawler with an acute tendency for developing parametric rolling. Many runs were done, both in regular and irregular waves, in order to determine how the different parameters involved, influenced the roll motion of the ship.

Moreover, the proposed forecasting system was tested against realistic conditions, in two different scenarios, taken from the towing tank tests described above; the first consisted in a regular wave case in which roll resonance was fully developed, while the second consisted in an irregular wave case.

Three test cases were considered, using the MPNN for making 10 seconds ahead predictions of roll motion. Although these tests showed very promising results, and support the idea of applying ANN for obtaining a parametric roll detection system, further work is needed to obtain accurate results in a longer time horizon.

5. ACKNOWLEDGEMENTS

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