Large Amplitude Roll Motion Forecasting through an Artificial Neural Network System

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ABSTRACT

Parametric roll detection systems have been stated as a need by the shipping industry, after some important incidents. They should predict, some time in advance, the onset of parametric roll, allowing the crew to take corrective actions.

A neural network based roll motion forecasting system, that could be used for predicting the appearance of parametric roll, is described in this work. It has been tested in two head seas scenarios, obtaining promising results. In the first one, the system is tested against a three d.o.f. nonlinear coupled model, while in the second one, towing tank experiments are used.

KEYWORDS

Parametric rolling; Neural networks; Time series forecasting; Ship stability.

INTRODUCTION

The well known phenomenon of parametric roll resonance has gained attention in the last few years, after some important episodes involving large containerships and passenger vessels; they resulted in very significant structural and cargo damages as well as in injuries to passengers and crew. Among these, the incidents of the APL China (1998) or Maersk Carolina (2003) containerships and the Grand Voyager (2005) and Pacific Sun cruise ships, case in which parametric roll may have been one of the causes of the three large amplitude roll cycles sustained in 2008, could be mentioned.

These types of ships, together with fishing and Ro-Ro vessels, are those most affected by this stability related phenomenon, that under certain conditions leads to very large roll motions.

These conditions include a head or stern seas situation, an encounter frequency approximately doubling natural roll frequency, wavelength similar to ship length, wave amplitude over a ship dependant threshold and some specific hull characteristics (present in the aforementioned ships), that include big bow flares and hanging sterns.

Once those conditions are present, parametric roll resonance could develop at any time; moreover, the onset of the phenomenom is very sudden, and very large amplitudes could be reached in just a few rolling cycles. This fact makes it very difficult for the crew to take any corrective or preventive action in order to pull the ship out of the risk area. So, the need for a system that could warn the crew about the future development of a parametric roll resonance episode, soon enough to act on ship heading or speed, or to trigger an automatic stabilization system, is clear.

As a first approach, onboard decision support systems were designed in order to define, in a medium time horizon, potentially “resonance risky” areas along the planned ship route, alerting the master about the possibility that, in those areas and based on ship conditions and weather forecasts, resonance could occur.

However, the shipping industry and the research community have stated new objectives for those systems, establishing the need for a short time resonance predictor that could allow the crew to take instantaneus measures against a certain, and not a potential, risk. It is in this new generation systems where the presented approach is framed.

In this line, the works of Holden et al. (2007), McCue and Bulian (2007) and Galeazzi et al. (2010) are the most representative. The first and second cases propose model based alternatives, while Galeazzi et al. take the signal based approach.

In the work presented here, Artificial Neural Networks (ANN) have been used as a roll motion forecaster, exploitong their capabilities as nonlinear time series predictors, in order to subsequently detect any parametric roll event through the analysis of the forecasted time series (Golden, 1996).

ANNs are biologically inspired algorithms that have the capability of modelling nonlinear systems after a process of training with a set of examples. Once trained, they can obtain accurate results from unknown inputs.

In this work, the training and testing proccesses have been carried out in two different scenarios. In the first one, a three Degrees Of Freedom (d.o.f.) coupled model, developed by Neves and Rodriguez (2006), has been applied for computing ship motions in heave, pitch and roll, in parametric rolling conditions in regular longitudinal seas. In this case, a model of a stern trawler with high tendency to developing parametric roll has been used.

In the second scenario, towing tank tests of a larger trawler have been conducted in order to obtain the ship motions, in similar conditions to those present in the first one (regular longitudinal seas), but also including non resonant conditions.

In both cases, a Multilayer Perceptron network (MP) has been used for forecasting the ship roll time series in different degrees of advance; its main structure (hidden layers, number of neurons), has been modified in order to obtain the better performance.

The results obtained both in the mathematical model case and in the scale tests are very promising, and showed good agreement between the forecasted and the real values for predictions of up to 10 seconds into the future.

FORECASTING SYSTEM

Artificial Neural Networks

ANNs are mathematical algorithms inspired by biological neural connections. Their main characteristic is their ability to learn a given behaviour, including nonlinear ones, from a set of examples, called training cases.

ANNs are made up of a set of interconnected neurons, arranged in layers, where the main computations are carried out. Each neuron input is weighed, a bias is added and finally the result is proccesed by an activation function and transferred to the next layer. Basically, the training proccess is carried out by feeding the system with a set of inputs and their corresponding outputs. The error between these outputs and the response generated by the ANN is computed, and the values of weights and biases are modified in order to minimize it.

Proposed Structure

In the presented work, the selected ANN structure is the well known MP architecture. The system is fed by a 20 seconds ship roll time series, sampled at 2 Hz, which corresponds to 40 network inputs. The system was designed to generate only one output, which is the roll value for the next time step. If this output is added to the input vector (substituing the first roll value), and the ANN is executed recursively, roll motion predicitons of any desired length could be obtained from the 20 second input set. Of course, the performance of the prediction will degrade with the number of iterations.

Taking into account that the number of hidden layers and neurons directly influence the performance of the system (the larger the number of neurons and layers, the better the performance, but only up to a limit), they have been modified in the different tests in order to obtain the best results, ranging from 2 to 3 hidden layers and from 30 to 50 neurons in each one of them.

RESULTS

Three d.o.f. Model

As a first approximation, training and test cases have been generated using a three d.o.f. mathematical model of a fishing vessel with a high tendency towards developing parametric roll resonance. This model has been developed by Neves and Rodíguez (2006) and has proven to accurately simulate parametric roll oscilations in regular head seas.

Mathematical Model

The aforementioned model computes heave, pitch and roll motions in a coupled way and is based on up to third order Taylor series expansions. It has been extensively studied, proving to precisely reproduce roll motion in parametric rolling conditions, in longitudinal and regular waves, for both a fishing vessel (Neves and Rodíguez, 2006) and a containership (Holden et al., 2007).

The details of the model could be found in Neves and Rodríguez (2006).

Ship Characteristics

The ship used as the first testing case is the well known trawler vessel studied in Neves and Rodríguez (2006). Its hull forms, that include an overhanging transom stern, make it very prone to developing parametric roll resonance. As has been previously mentioned, fishing vessels are among those ship types where parametric roll is more frequent. Moreover, and due to their reduced stability levels and poor crew training, they could be the type of ship where a parametric roll warning system could have more importance from the safety point of view. In Table 1, the main characteristics of the ship are described. Speed and loading condition parameters have been kept constant in all experiments.

Test Cases

In order to test the capacity of the proposed system to forecast ship roll motions, the following tests have been conducted.

Parametric roll is usually triggered when certain conditions are fulfilled simultaneously. On one hand, ship – wave encounter frequency should be about double the ship natural roll frequency. Taking into account that in our case ship speed, loading condition and heading (head seas) are kept constant, wave frequency is the only variable influencing encounter frequency. On the other hand, wave amplitude should be above a given threshold, which is ship dependant.

Table 1: Test vessel 1 main characteristics

Overall Length	25.91 m
Breadth	6.68 m
Depth	3.35 m
Displacement	170.3 t
Metacentric Height	0.37 m
Natural Roll Frequency	0.858 rad/s
Froude Number	0.3

In this first test, 200 second roll motion time series have been obtained from 49 combinations of wave frequency and wave amplitude, where parametric roll resonance occurs, and have been truncated when steady state was reached. Wave amplitude ranges from 0.33 to 0.6 m, while frequency ratio ranges from 1.917 to 2.504 rad/s. 2660 training cases have been obtained by dividing the 49 roll time series into groups of 40 inputs and their corresponding output.

With the described training process, the system should be able to predict the behaviour of the ship sailing in any of the wave conditions situated inside or in the surroundings of the rectangle limited by the aforementioned values. Test cases were chosen between these values; the two test combinations are presented in Table 2.

Table 2: Test series selected parameters

Case	$\omega_w\ (rad/s)$	$\omega_e\ (rad/s)$	ω_e / ω_n	$A_w\ (m)$
1	1,200	1,848	2,154	0,41
2	1,320	2,104	2,453	0,345

In the following section, results obtained for 5, 10 and 40 second ahead predicitons with two different MP structures are presented. Both structures have two hidden layers, but the number of neurons has been increased, going for 30 neurons per layer in the first case to 40 in the second.

Results

In Figures 1 and 2, the results obtained with the 40 neuron MP network, in the 5, 10 and 40 second predictions are presented, while in Tables 3 and 4, the error values of the predicitions (mean squared error, MSE) obtained with both the 30 and 40 neuron MPs are described.

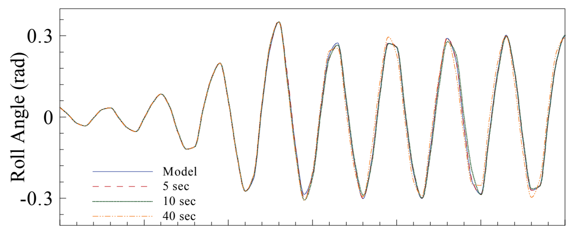

Fig. 1: Test 1. Forecast results. 40 neurons, 2 layer MP.

Table 3: Test 1. Predicton performance. MSE (x10^{-4})

Prediction Horizon	30-30	40-40
5 seconds	0.19	026
10 seconds	0.65	0.85
40 seconds	722.00	378.43

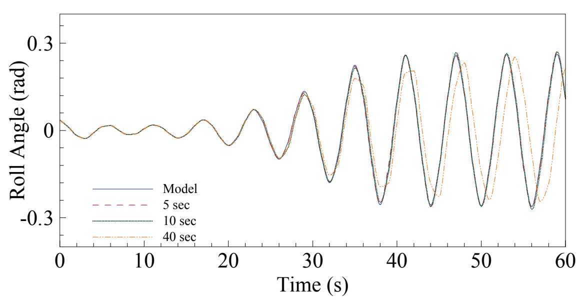

Fig. 2: Test 2. Forecast results. 40 neurons, 2 layer MP

Table 4: Test 2. Predicton performance. MSE (x10^{-4})

Prediction Horizon	30-30	40-40
5 seconds	0.42	0.29
10 seconds	2.01	0.90
40 seconds	664.12	529.69

As shown in the previous figures, the forecasts generated by the system track the model very accurately, even in predictions of up to 40 seconds in advance, especially in the test case number 1. Observing the values of the MSE for both cases, it can be concluded than results obtained with the larger MP are better than those obtained with the 30 neuron one, except for the 5 and 10 second predicitions in the test case number 1, where both are very similar.

Although these results are very good, it is obvious that they are limited to a reduced experimental window; training has been performed only considering conditions where parametric roll was present, with the ship sailing in pure longitudinal waves and with no external uncontrolled disturbances present (as a mathematical model is being used). Parametric roll fully develops in a few rolling cycles and then the steady state is indefectively reached.

TOWING TANK TESTING

In order to test the behavior of the proposed system in a more realistic scenario than that provided by the mathematical model, scale model towing tank tests have been conducted. In these tests, the ship is towed along the tank in regular longitudinal waves, in 6 d.o.f. In this case, the ship is under the influence of the disturbances generated by the carriage, wave interferences, wave iregularities generated by the wave-maker, etc.

Following the same methodology as described for the mathematical model case, roll time series have been obtained by carrying out seakeeping tests in head regular seas, that have been used for training and testing the ANN forecaster. In order to evaluate the performance of the algorithm both in conditions where parametric rolling occurs and where it doesn´t, non resonant situations have also been included.

Ship Characteristics

In this second experiment, another fishing vessel has been selected. It is a larger stern trawler, also with an acute tendency towards developing parametric roll resonance in not very heavy seas, mainly due to its transom stern hull forms. This ship has been studied by de Juana Gamo et al. (2005) and its main characteristics are described in Table 5. A 1/18.75th scale model has been used for the towing tank experiments.

Table 5: Test vessel 2 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
Froude Number	0.2

Test Cases

To obtain training and test cases, 16 experiments have been carried out with different values of wave frequency and amplitude, with an average full scale length of 420 seconds. Encounter frequency – natural roll frequency ratio ranges from 1.8 to 2.3, implying that there would be cases where parametric roll is not present. This fact allowed us to evaluate 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 appart from head waves). Experimental conditions are shown in Figure 3. From those 16 experiments, two time series were chosen for testing the system (blue dots in Figure 3), including one with fully developed parametric roll, and another one without any resonant motions.

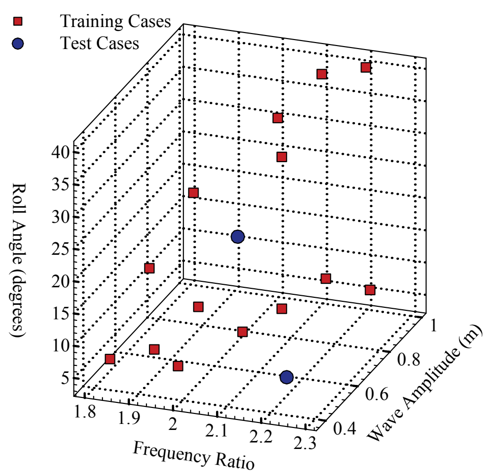

Fig. 3: Towing tank experiments. Parameters.

During the experiments, time series were sampled at a frequency of 50 Hz. For generating the ANN training 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.

Taking into account that realistic data implies the need of a more complex model for obtaining good results, the MP structure used with the mathematical model, was modified; different alternatives were tested, both increasing the number of neurons and the number of layers. The results obtained are presented in the following section.

Results

As previously described, two test cases have been proposed, for combinations of wave frequency and amplitude not used during the training phase. The first one (Test 1), corresponds to a frequency ratio of 2.0 and a wave amplitude of 0.745 m (fully developed resonance). In the second one (Test 2), a frequency ratio of 2.2 and a wave amplitude of 0.5 m (no resonance condition) have been selected.

In order to increase the precision of the system, five different MP structures have been tested; a two hidden layer alternative, with the number of neurons ranging from 40 to 50, and a three layer alternative with 30 and 40 neurons per layer. 10 seconds ahead predictions have been conducted for all test cases.

In Table 6, the error values (MSE), obtained with the five different MP structures for the two test cases, are presented. In Figures 4 and 5, the results obtained with the best alternative for each of the test cases (three layers and 30 neurons per layer in Test 1, and three layers and 40 neurons per layer in Test 2), are included.

Table 6: Tests predicton performance. MSE (x10^{-4})

Test case	40-40	45-45	50-50	30-30-30	40-40-40
1	15.38	16.47	16.55	12.04	15.05
2	4.11	4.20	4.33	4.73	3.76

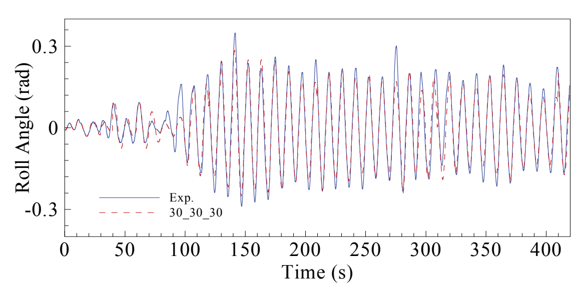

Fig. 4: Test 1. Forecast results. 30 neuron, 3 layer MP.

It has to be emphasized that ANN performance increases with the number of layers and neurons, but up to a limit, over which its performance remains constant. This fact could be appreciated in the two hidden layer alternatives, where in both cases, the best results are obtained with the 30 neuron structure, and also in the three hidden layer alternative in Test 1, where the best results correspond to the 30 neurons case.

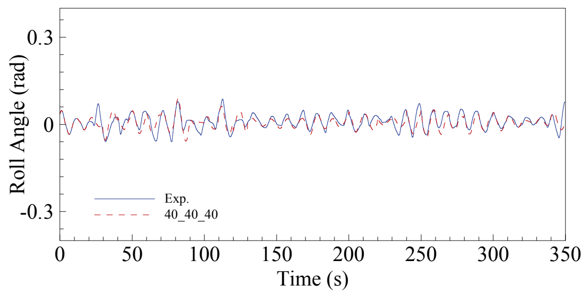

Fig. 5: Test 2. Forecast results. 40 neuron, 3 layer MP.

CONCLUSIONS

In this work, an application of ANN as ship roll motion forecasters has been presented. Training and testing of the system has been done using both a mathematical model and scale model testing, with two different fishing vessels, for longitudinal regular head seas in resonant and non resonant conditions.

The results obtained in the mathematical model case present accurate predictions of up to 40 seconds ahead. Considering the roll period of the ship (of about 7.3 seconds), and after being analyzed by a parametric roll detection system, they could be long enough for alerting the crew and allowing them to take corrective actions. However, it should be stated that this was an ideal case, and results would decrease in precision in a more realistic scenario.

This scenario was presented in the results obtained with the towing tank experiments. In this case, accurate predictions have been obtained of up to 10 seconds ahead. Considering the fact that the roll period of the tested vessel is around 11.2 seconds, the obtained results could be used for triggering an automatic prevention system, but seems to be short for allowing a manual response. However, further developments are being undertaken for obtaining more precise longer predictions, both in regular and also in irregular seas.

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