Experimental Analysis of Roll Damping in Small Fishing Vessels for Large Amplitude Roll Forecasting

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ABSTRACT

In this paper, the practical implementation methodology of an artificial neural network (ANN) based parametric roll prediction system, is studied. In order to avoid expensive scale tests, an uncoupled nonlinear roll model is applied to tune the system. To validate this model, together with the selected roll damping approach, a towing tank test campaign has been carried out. Finally, the behaviour of the ANN system for forecasting roll motion from a realistic sailing condition, obtained from the towing tank campaign, has been investigated, obtaining very promising results.

KEYWORDS

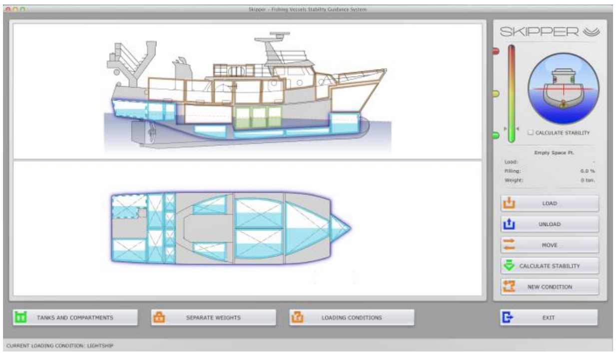
Parametric rolling; Neural networks; Time series forecasting; Ship stability.

INTRODUCTION

Fishing represents one of the industrial sectors where occupational accidents are more frequent. In fact, fishing is considered as one of the most dangerous activities worldwide. For example, it ranks first in fatal injury rates in the U.S. (BLS, 2012) and in Great Britain (Womack, 2002), and second in Spain (MTI, 2009).

Most of the human losses occur due to ship related events, such as stability issues, grounding, falling objects, etc. Among them, incidents due to stability failures (i.e. capsize or large heel) account for the majority of the casualties (more than a half in Spain, for example (Artai, 2001)), especially in small ships. This could be explained by the fact that very often these accidents develop very fast and because they usually imply the complete loss of the vessel.

Small and medium length vessel skippers base their capability for evaluating the stability of their ships mainly in previous experience, which usually doesn't include important incidents. In addition, they are under trained for adequately understanding the information contained in the stability booklets, which is, in fact, the only help they have for evaluating the intact static stability of the ship in a given sailing condition. An even more dramatic situation shows up when talking about dynamic stability issues. Considering that in most cases the phenomena of this sort are completely unknown to the skippers, it is impossible that they could face them correctly in order to avoid their consequences. All these issues, together with the fact that they need to fish even under very rough weather conditions and other circumstantial factors, are the main causes of such accidents. The few known published works aiming at developing stability guidance tools for the skippers, thus providing objective information about the safety of their ships, range from simple stability posters or displays to computer on-board systems (Gudmundsson, 2009). In this last approach, some of the authors of this work have proposed their own alternative.



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CURRENT LOADING CONDITION: LIGHTSHIP

Fig. 1: Fishing vessel stability guidance system screenshot.

It provides the minimum essential information related to the stability of the vessel in the current loading condition, in a very clear and understandable way, even for users with no specific training in the use of computer software (Míguez González, Caamaño Sobrino et al., 2012).

However, this system is based on the analysis of static stability criteria (IMO intact stability requirements) and dynamical effects, such as parametric roll resonance, broaching or pure loss of stability, which are also of paramount importance on the safety of fishing vessels, have not been considered yet.

As it is well known, parametric roll is a phenomenon which affects fishing vessels, among other types of ships, and that may generate very large amplitude roll motions in a very sudden way, deriving in heavy damage or even in capsizing.

In the last years, the authors have been working on the development of a prediction system, which would alert the crew about the immediate appearance of an episode of parametric rolling and allow them to take preventive actions. The selected approach was based on the use of artificial neural networks (ANN), which have shown to work satisfactorily in many conditions. To start with, the system has been tested to predict the development of parametric rolling from data generated by a model of ship motion with three degrees of freedom. Next, the predictions where made with data obtained from towing tank tests, which represented a more realistic approach (Míguez González, Díaz Casás et al., 2012).

However, cost is always an important factor when it comes to the application of the system to any ship. The need of carrying out a towing tank test campaign prior to its installation onboard, with the objective of obtaining the training data for the ANN system, implies a large cost and complicates the adaptation of the system to each ship, especially in the case of a small ship

This paper presents some of the works oriented to define the practical implementation methodology of these prediction schemes within the aforementioned stability guidance system.

In order to reduce the cost of fitting the system to each ship, a 1.5 degrees of freedom mathematical model has been used to tune the prediction system, instead of using towing tank tests data. The performance of this model to accurately reproduce the roll motion of a medium sized trawler has been validated itself by using data from towing tank tests. Moreover, roll damping tests have also been carried out, in order to verify the adopted nonlinear roll damping model approach.

Finally, the performance of the mathematical model-tuned forecasting system to predict the appearance of parametric roll in a realistic seaway is presented. In order to do this, some results obtained from the proposed parametric roll forecasting system, tested against roll motion data obtained during towing tank tests campaigns, are presented.

MODEL TESTS

The ship under analysis is a medium sized stern trawler having an acute tendency towards developing parametric roll resonance even in not very heavy seas. This trend is caused, in part, by 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.

In this test campaign, 68 time series describing the ship roll motion during the tests have been obtained, covering different combinations of wave frequency, amplitude and ship speed (frequencies ratio between 1.7 and 2.3, wave heights between 0.5 m and 3 m and ship speeds such as to have Froude numbers (Fn) between 0 and 0.3).

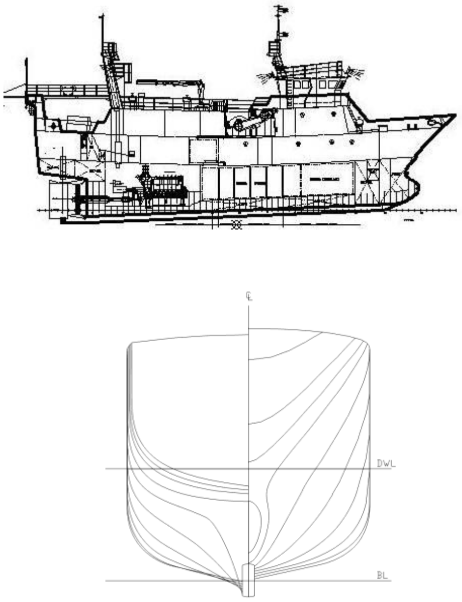

Fig. 2: Stern trawler arrangement and hull forms.

Table 1: Test vessel main characteristics.

Overall Length	34.50 m
Beam	8.00 m
Depth	3.65 m
Displacement	450 t
Metacentric Height	0.350 m
Natural Roll Frequency (ω_ϕ)	0.563 rad/s

These conditions include cases where parametric roll resonance is present and others when it is not. Wave length is determined as a function of wave frequency, under the deep waters approach.

In addition, still water roll decay tests have also been accomplished at four different forward speeds (corresponding to Froude numbers ranging from 0 to 0.4) and different initial roll angles. These tests are used for determining the roll damping coefficients that are used in the mathematical model.

MATHEMATICAL MODEL

In order to tune the prediction system, in a simple and non expensive way, it was necessary to define a mathematical model able to adequately reproduce the behaviour of the ship in parametric roll conditions, but minimizing the number of parameters that have to be computed to fit the model to other different ships.

In this work, the 1 degree of freedom nonlinear uncoupled roll model proposed by Bullian (2006) has been adopted. On it, the time varying nonlinear roll restoring term needed for stimulating parametric roll is computed taking into account the quasi-statical effects of heave and pitch motions in roll. The proposed model has the following structure:

$$(I_{xx}+A_{44})\cdot\ddot{\phi}+B_{44,T}(\dot{\phi})\cdot\dot{\phi}+C_{44}(\phi,t)=0 \qquad (1)$$

Where I_{xx} and A_{44} are respectively the mass and added mass moments of inertia in roll, $B_{44,T}(\dot{\phi})$ represents the nonlinear damping term and $C_{44}(\phi,t)$ is the time varying nonlinear restoring coefficient. As it is generally accepted, the added mass term A_{44} has been obtained by potential theory methods. The computation of restoring and damping terms is described in the following subsections.

Restoring arms

As have been mentioned above, the influence of pitch and heave motions, together with wave passing along the hull, has to be taken into account for an accurate simulation of parametric roll. Considering that the proposed model doesn´t include the coupling between roll and heave and pitch, both effects have been taken into account in a quasi-static way within the restoring term.

In order to do this, the "look up table" approach, described by Bullian (2006) and required by the American Bureau of Shipping (ABS) in 2004 for modelling the variation of the ship restoring capabilities in longitudinal waves, was applied for computing the restoring term $C_{44}(\phi,t)$. Under this approach, for each wave crest position and roll angle, trim and sinkage are able to change up to a static stability position, while heave and pitch motions are statically balanced. This method has demonstrated to perform well in following seas and in head seas with wavelengths longer than ship length (where heave and pitch motions are supposed to be quasi-static). Additionally, in Bullian (2006), its application to wavelengths similar to wavelengths in head seas, was also successful.

For each set of wave parameters (height and wavelength) and for the different positions of wave crest along the hull, the GZ curves were computed applying classical hydrostatics under free trim conditions. In order to obtain the time dependant restoring coefficient $C_{44}(\phi,t)$, the aforementioned wave crest domain GZ curves, were transformed to the time domain by considering the wave encounter frequency.

An example of the results of these GZ computations, corresponding to a wavelength of 40 meters and a wave height of 2 meters, are displayed and compared to the still water case on Figure 3. On Figure 4, the interpolated GZ surface for this same case and the different wave crest positions is presented.

Roll damping

One of the most critical elements for ensuring a good simulation of roll resonance is the modelling of roll damping because it is highly nonlinear in the large roll amplitudes present during parametric resonance.

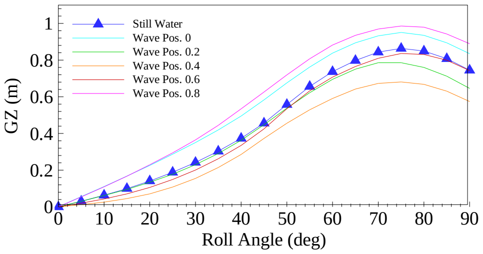

Fig. 3: GZ curves as a function of wave position. 0, wave crest in Fwd Pp. 0.5, wave crest amidships. λ=40 m. H_w= 2 m.

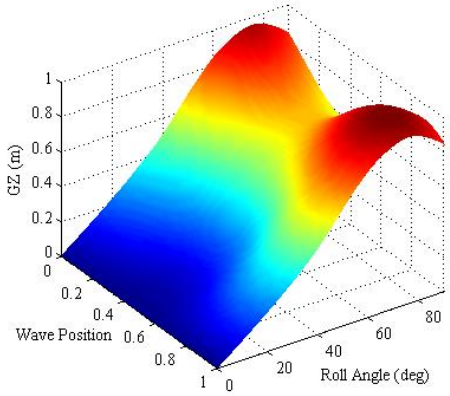

Fig. 4: GZ variation due to wave passing. λ=40 m. H_w= 2 m.

In order to account for these nonlinearities, a nonlinear quadratic approach has been adopted, decomposing roll damping in a linear and a quadratic term.

This same approach has been broadly applied in other works dealing with parametric roll modeling, i.e. (Neves, 2006).

According to this structure, the ship roll damping would remain as:

$$B_{44,T}(\dot{\phi})\cdot\dot{\phi} = B_{44a}\cdot\dot{\phi} + B_{44b}\cdot\dot{\phi}\cdot\left|\dot{\phi}\right| \tag{2}$$

In order to obtain the linear ($B_{44,a}$) and nonlinear ($B_{44,b}$) coefficients, still water roll decay tests for different forward speeds and initial roll angles have been carried out. The procedure followed for determining the damping coefficients from these tests, is that described in Himeno (1981).

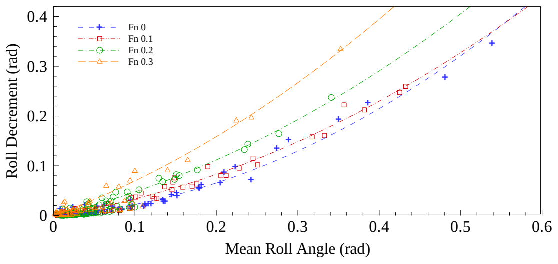

Fig. 5: Roll decrement data (scatter points) and fitting quadratic polynomial (lines) from roll decay tests.

In Figure 5, the results of roll decrement as a function of mean roll angle are presented, together with a quadratic fitting, for the whole set of data points obtained in the roll decay tests at the four forward speeds.

Table 2: Non-dimensional damping coefficients.

Froude Number	ν	β
Fn 0	0.0187	0.3932
Fn 0.1	0.0404	0.3008
Fn 0.2	0.0620	0.3158
Fn 0.3	0.0953	0.3631

In Table 2, the obtained damping coefficients at the four Froude numbers are shown, in the form of non-dimensional damping coefficients, defined by:

$$2\cdot\nu\cdot\omega_{\phi}=\frac{B_{44a}}{(I_{xx}+A_{44})};\beta=\frac{B_{44b}}{(I_{xx}+A_{44})} \qquad (3)$$

Moreover, and for the sake of comparison, the damping moments obtained by using the damping coefficients from the roll decay tests and those computed by using the Ikeda approach, for the zero speed case, are presented in Figure 6.

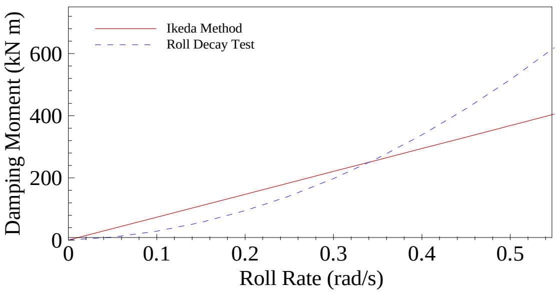

Fig. 6: Roll damping moments comparison. Fn = 0.

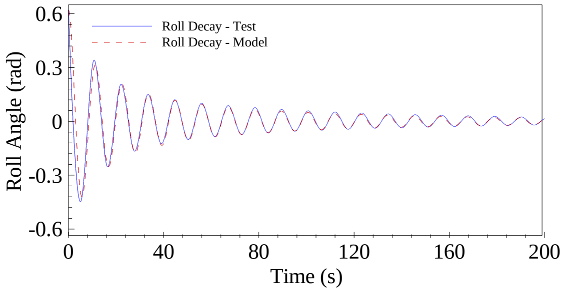

Fig. 7: Roll decay tests. Fn = 0.

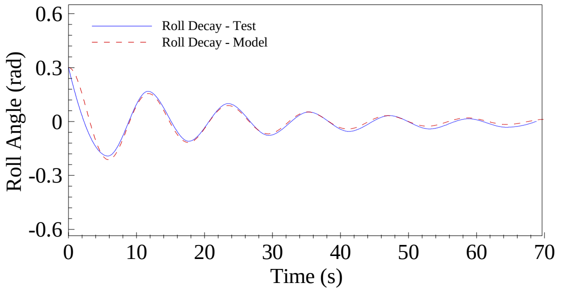

Fig. 8: Roll decay tests. Fn = 0.3.

The validation of the damping coefficient results has been done by comparing the towing tank results to those obtained by using the mathematical model.

In Figures 7 and 8, the results corresponding to forward speeds of Fn=0 and Fn=0.3 are presented. As can be appreciated, the mathematical model data accurately fit the towing tank results.

Model Validation

In this section, the performance of the model for accurately simulating the roll motion of the ships in the different sailing conditions, including those where parametric rolling is present, is analyzed.

The data used for the validation process are those obtained from the towing test campaign that has been already described, including runs at different forward speeds, wave frequencies and wave heights.

In Figures 9 and 10, some examples of the performance of the model are presented. On them, the roll motion time series obtained with the proposed mathematical model, for conditions likely to induce parametric roll, are compared to the corresponding results from the towing tank experiments. These conditions include encounter frequency – natural roll frequency ratios of 2.0, wave heights of 1.491 m and forward speeds of Fn 0 and 0.1.

Observing the results displayed in the figures above, it can be concluded that the correspondence between simulated and towing tank test data is quite good, both in the initial transient stage and in the steady state motion; however, a slight underestimation of the roll amplitude has been observed, not only in the two presented cases, but also in the rest of the compared time series at these two speed values. This issue is more noticeable as speed increases, as could be appreciated in Figure 9; in fact, the model is unable to reproduce any of the parametric roll events which occur for the higher speeds of Fn 0.2 and Fn 0.3, where lower wave frequencies imply much longer wavelengths.

This behavior may be related with the quasi static approach adopted for the computation of the time varying restoring term. From the towing tank tests experiments, it has been observed that heave and pitch motions were of quite large amplitude in these conditions, and that they influence in the developing of parametric roll was much higher than that predicted by the quasi static approach.

However, and in order to illustrate the performance of the parametric roll prediction system, only conditions of up to Froude 0.1, where the mathematical model has demonstrated to work fine, have been used.

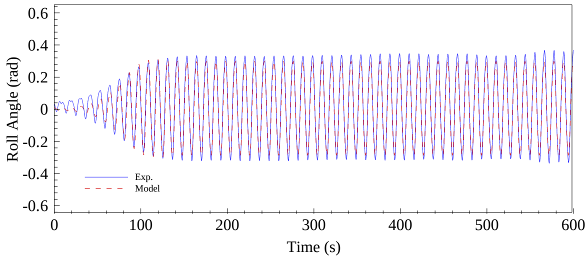

Fig. 9: Roll data. Fn = 0. Frequency Ratio = 2.0. Hw = 1.491 m. λ = 48.640 m.

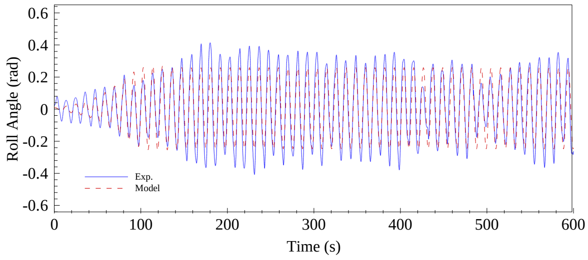

Fig. 10: Roll data. Fn = 0.1. Frequency Ratio = 2.0. Hw = 1.491 m. λ = 66.145 m.

PARAMETRIC ROLL FORECASTING SYSTEM

Developing a parametric roll prediction system, which alerts the crew and allows them to take corrective actions before it develops, is an issue which has gained a lot of attention in the last years, due to the increase in size and number of ships likely to suffer from the phenomenon. Among the published alternatives, the one by Galleazzi et al. (2012) is the only under real scale testing nowadays.

On the other hand, the authors of the present work have been working on the development of a roll forecasting system, based on the application of Artificial Neural Networks (ANN) in addition to the single detection provided by the system above. This ANN system will add the knowledge of the evolution of the roll motion time series with some time in advance. This will provide, among other advantages, data for increasing the performance of possible corrective actions (Míguez González, Díaz Casás, et al., 2012). The ANNs are mathematical algorithms which have the property of acting as very good nonlinear estimators after an adequate training process.

The structure of an ANN consists of an input layer, which receives the data, a series of hidden layers, where the so-called neurons are included, and an output layer. Neurons are in charge of processing the data by weighing, biasing and summing up the input data they receive, processing them with an activation function and sending them to the following neuron. The process of training consists of feeding the network with known data of the behavior of the system that wants to be modeled, and selecting the weights and biases which minimize the errors between real and predicted outputs (Haykin, 1999).

Until now, the authors have applied this method to forecast the ship roll motions obtained both with a 3 degrees of freedom model and with towing tank tests, in regular and irregular head seas. The training data has been obtained in the same way in both cases: from the mathematical model in the first one, and from the towing tank tests in the second. However, the main objective is to implement the proposed system onboard of new and existent ships at a reduced cost. Thus, carrying out a large towing test campaign to train the ANNs prior to its installation is not a suitable alternative.

So, in this work the application of mathematical model trained ANN´s to forecasting ship roll motions obtained from towing tank tests is analyzed. This way, the only need when setting up the system on a ship will be to compute the mathematical model parameters and then use it to train the networks, with no need for complex towing tank testing. This approach would represent the practical way of implementing the system in a real case.

The selected ANN structure is that of a multilayer perceptron network with three hidden layers, 30 neurons per layer, and one output layer. The input vector is composed by 40 elements, representing 20 seconds of the roll motion time series. The output is composed by only one element, being it the prediction one step ahead. Substituting the output value within the input vector and recursively executing the algorithm, predictions in different degrees of advance can be obtained.

The training data consisted on 56 time series of roll motion, obtained with the mathematical roll model at different combinations of wave frequency and height and for a forward speed of Fn 0.1. The selected parameters are included in Table 3. This data set not only includes the area where resonance is most probable, but also regions where resonance doesn't develop.

In order to test the system, two time series, where parametric roll takes place, have been selected from the towing tank tests described in preceding sections. The parameters of these time series are included in Table 4. In both cases, the forecasting system has been executed to obtain predictions 10 seconds in advance, which approximately represent one whole roll period. The obtained results are presented in Figures 11 and 12. The Mean Squared Error (MSE) of the predictions is included also in Table 4.

Table 3: Training data parameters.

Froude number	0.1
Wave frequency range	0.8 – 1.2 rad/s
Frequency ratio range	1.6 – 2.6
Wave height range	0.5 – 2.5 m

Table 4: Test data parameters and MSE results.

	Test 1	Test 2
Froude number	0.1	
Wave frequency	0.965 rad/s	
Frequency ratio	2.0	
Wave height	1.491 m	1.988 m
MSE x 10^{-4}	442.00	504.14

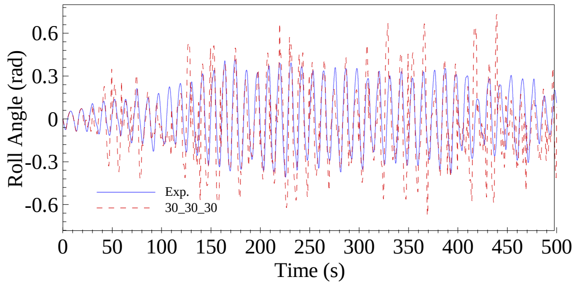

Fig. 11: Test 1. Prediction results.

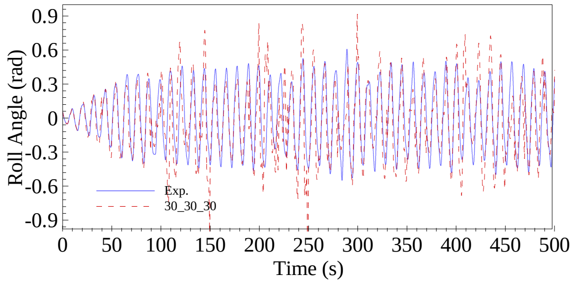

Fig. 12: Test 2. Prediction results.

Analyzing the obtained results, it can be seen that the forecasting system correctly tracks the onset of the phenomenon in both test cases. However, as roll motion amplitude increases, some overpredictions are observed, which are especially relevant in Test 1. If the system is applied only for detecting the appearance of the phenomenon, these overpredictions won´t be very relevant, as they won´t imply a misdetection or false alarm. Nevertheless, if forecasted roll motion is needed for establishing preventive measures, it is necessary to improve the performance of the system in order to avoid these peaks in the predicted roll motion.

CONCLUSIONS

This work presents some of the activities carried out by the authors for implementing a parametric roll prevention system based on the use of Artificial Neural Networks within an onboard stability guidance software. This system is primarily focused on providing stability information to the skipper of small and medium sized fishing vessels. The main requirements of such a system are ease of use and installation, and low cost. These requirements make the use of towing tank test campaigns not a feasible option for training the forecaster. The presented approach relies on the use of a mathematical model to train the ANNs for forecasting roll motion in realistic sailing conditions.

In order to do this, a one degree of freedom nonlinear roll model of a medium sized trawler, where pitch and heave effects on roll are taken into account in a quasi–static way has been developed. Moreover, a nonlinear quadratic approximation of roll damping term has been selected. The capacity of this model to accurately reproduce parametric roll resonance in different conditions of wave frequency, wave height and ship forward speed, has been analyzed by comparing the results obtained with the model against those obtained from a towing tank test campaign. In addition, roll decay tests in still water have been carried out to define the components of the quadratic damping.

The proposed model has shown a good performance for simulating parametric rolling at small forward speeds (up to Fn 0.1). However, at higher speeds the model is unable to simulate the large coupling between heave, roll and pitch observed in the tank tests and the parametric rolling events that were observed in them.

Once the model behaviour has been analyzed, it has been applied for computing the ANN training data, including different combinations of wave parameters. The selected speed corresponds to a Fn = 0.1, at which the proposed forecasting model showed to be accurate.

With the objective of testing the system in a realistic situation, two time series where parametric roll is completely developed, have been selected from the Fn 0.1 tank test results and the forecaster was executed in order to obtain 10 seconds in advance predictions. The obtained forecasts are quite accurate in both test cases, especially during the transient period in which resonance develops, although some overpredictions were observed during the steady state phase.

Regarding the prediction horizon, it is necessary to improve this value because 10 seconds (1 roll period) could be enough for triggering automatic corrective actions in the type of vessels analyzed in this work; but they seem to be too short if these corrective actions have to be undertaken by the crew.

In any case, the obtained results empower the idea of applying mathematical model trained artificial neural networks, for parametric roll prediction, with no need of expensive and tie consuming towing tank tests. Nevertheless, further research is needed to improve the performance of the forecaster during the steady state phase, and also to increase the prediction time horizon.

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REFERENCES

American Bureau of Shipping (ABS), Guide for the assessment of parametric roll resonance in the design of container carriers, 2004.

Artai, Correduría de Seguros S.A., Siniestralidad de los marineros gallegos en el período 1991 – 2000, 2001.

Bureau of Labor Statistics (BSB), National census of fatal occupational injuries in 2011, U.S. Department of Labor, 2012.

Bulian, G., Development of analytical nonlinear models for parametric roll and hydrostatic restoring variations in regular and irregular waves, PhD Thesis, Universitá Degli Studi di Trieste, Trieste, Italy, 2006.

De Juana Gamo, J., Arias Rodrigo, C., Pérez Rojas, L., On the parametric rolling of fishing vessels, 1st International Conference on Marine Research and Transportation, 2005.

Galeazzi, R., Blanke, M., Poulsen, N. K., Early detection of parametric roll resonance on container ships, IEEE Transactions on Control Systems Technology, PP (99), 2012.

Gudmundsson, A., Safety practices related to small fishing vessel stability, Food and Agriculture Organization of the UN, 2009.

S. Haykin, Neural networks: a comprehensive foundation, Prentice Hall, 1999.

Himeno, Y. , Prediction of ship roll damping. A state of the art, Department of Naval Architecture and Marine Engineering, The University of Michigan College of Engineering, Michigan, USA, 1981.

Míguez González, M., Caamaño Sobrino, P., Tedín Álvarez, R., Díaz Casás, V., Martínez López, A., López Peña, F. , Fishing vessel stability assessment system, Ocean Engineering, 41, 67-78, 2012.

Míguez González, M., Díaz Casás, V., López Peña, F., Pérez Rojas, L., Experimental parametric roll resonance characterization of a stern trawler in head seas, 11th International Conference on the Stability of Ships and Ocean Vehicles, Athens, Greece, 2012.

Ministerio de Trabajo e Inmigración (MTI), Estadística de accidentes de trabajo y enfermedades profesionales, Annual data, 2009.

Neves, M. A. S., Rodríguez, C. A., On unstable ship motions resulting from strong non-linear coupling, Ocean Engineering, Vol. 33, pp. 1853-1883, 2006.

Womack, J., Small commercial fishing vessel stability analysis. Where are we now? Where are we going?, Proceedings of the 6th International Ship Stability Workshop, Webb Institute, 2002.