NUMERICAL AND EXPERIMENTAL STUDY OF THE PARAMETRIC ROLLING OF A FISHING VESSEL IN REGULAR HEAD WAVES

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SUMMARY

The dynamic behaviour of a fishing vessel in waves is studied in order to reveal its parametric rolling characteristics. This paper presents experimental and numerical results in longitudinal regular waves. The experimental results are compared against the results of a time-domain non-linear strip theory model of ship motions in six degrees-of-freedom. These results contribute to the validation of the parametric rolling prediction method, so that it can be used as an assessment tool to evaluate both the susceptibility and severity of occurrence of parametric rolling at the early design stage of these types of vessels.

1. INTRODUCTION

Parametric rolling has been studied since the early fifties by several investigators [1, 2, 3] and also by safety authorities [4]. However, it has been usually considered mostly of theoretical interest and less worthy of practical concern. More recently, the evidence of parametric rolling has gained practical importance after a post-Panamax container vessel encountered problems and was investigated by [5].

Despite the fact that certain types of container vessels are susceptible to parametric rolling, they are not the only type of vessel that requires attention. Fishing vessels, having a different hull form in comparison to container vessels, may also be susceptible to parametric rolling. The environment in which they operate imposes considerable difficulties to the crew onboard. If these conditions are made more severe, serious problems that endanger safety may arise. The problem of fishing vessel's parametric rolling was noted by [6], and further studied by [7]. In a recent project, the dynamic behaviour of fishing vessels has been studied further examining ships from the Portuguese, Spanish and Peruvian fleet's susceptibility to dynamic instabilities in waves [8, 9, 10, 11, 12].

To avoid parametric rolling, certain design measures need to be taken. Furthermore operational measures are also required and it may be possible to have a decision support system that provides assistance to the shipmaster [13]. However, in order to be considered reliable, all mathematical models need to be validated by comparing them to experimental data.

Bearing this aim in mind, this paper presents experimental measurements of parametric rolling of a fishing vessel in regular head waves and compares them with numerical predictions. The numerical model employed has been extensively tested for different hull forms [14]. See for example [15], where numerical predictions of two slender containerships and a bulky fishing trawler prone to parametric rolling in regular and irregular waves have been compared with experimental measurements available. This paper aims to further analyse results for that same bulky form of a transom stern fishing trawler under parametric rolling in regular head waves by addressing the decay of roll amplitude at the range of higher waves.

2. THE MATHEMATICAL MODEL

It has been demonstrated among others, by [16] that both linear and non-linear theories can be used to predict parametric rolling. The linear model is in form of a Mathieu equation. The model has not proved accurate enough to predict the ship's roll motion amplitude due to its limitations in taking factors such as deck submergence into account. Further development led to considering a nonlinear model with one degree of freedom, where an uncoupled roll equation, which included the effects of heave and pitch responses in regular waves and immersed hull variations due to wave passage on roll restoring term, was used to describe the roll motion. This model has provided a good agreement between the existing experimental data and the simulations. However, it did not make it possible to do calculations on irregular waves for the reasons that were presented in the literature by [17, 18, 19] at the time.

In order to simulate unidirectional long crested irregular wave responses of the vessel in the time domain, which are of greater practical interest to masters and operators, a more sophisticated model was then proposed by [20]. Subsequently, the model has been extended to include six degrees of freedom, with the addition of surge motion, using a semi-empirical formulation [21].

The program starts by calculating the frequency dependent hydrodynamic coefficients for 2D sections that result from a strip theory formulation. These coefficients are used in the time domain simulation of the ship motions. Application of the strip theory code's results to parametric rolling has been further discussed by [22].

Recently, an intermediate program that allows the use of this code in successive time domain runs from different values of governing parameters was developed [23]. This expansion also allows the use of different roll damping models, including the integration of experimentally obtained values provided by decay tests. In terms of roll damping estimation method, since most depend on the estimated maximum roll amplitude, the code mentioned above provides iterative calculations that stay within a user defined precision value. Finally, the initial trim and initial sinkage values are calculated using the input of the frequency domain program, so they are the calculated values for the start of the time simulation. The behaviour of the vessel is affected by the couplings. Therefore estimating the initial values of heave and pitch are important in terms of estimating the coupled roll motion.

3. EXPERIMENTAL PROGRAM

The experimental work was carried out at the ETSIN regular waves towing tank, in Madrid. The tank has 3.8 meters of width and 100 metres of length, with 2 metres of water depth. The towing platform is supported by two rails, and is able to reach speeds up to 3.5 metres per second. The wavemaker is capable of producing wave amplitudes up to 0.20 metres and the wave periods between 0.5 to 2.5 second. At one end of this tank there is a beach that allows the waves to dissipate and avoids wave reflection. The angle of inclination of the beach is 30 degrees and its efficiency was sufficient for the experiments described. The depth of the tank is larger than two times the wavelength of the tested waves, and therefore any shallow water effects were avoided.

Most of the required instrumentation to take measurements of the motion (accelerometers, inclinometers) was already available at the tank for the experiments. The data acquisition system to convert the analogue signals to digital has been developed at ETSIN. It consists of 12 channels of data, and has its own management software. Before the experiments, it was calibrated to ensure correct measurement of the waves, motions, and speeds. The range for linear motions is ±150mm. and 6 Kg for the rotational motions about the three principal axis, ±45 degrees and 15 Kgcm.

3.1 MAIN CHARACTERISTICS OF THE VESSEL

The Spanish vessel is a wood construction transom stern fishing trawler whose main particulars and lines plan are shown in Table 1 and Figure 1, respectively. It is visible in Figure 2 that the vessel has a transom stern, a large skeg and a small bulbous bow at aft and fore extremities.

The model scale is 1:18.75. The superstructure of the model has been opened in the middle to allow easier access to the inclinometer, which was installed at a point that coincided with the centre of gravity of the vessel. Weights of 15grams were used to obtain the same loaded condition of the vessel to be used in the parametric rolling tests. The total weight of the model is around 70 kilograms.

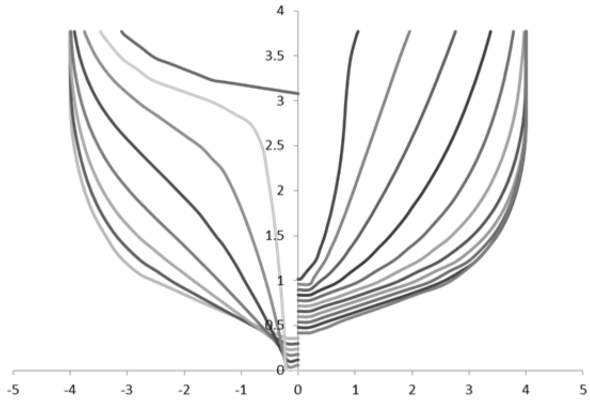

Figure 1: Underwater geometry of the vessel

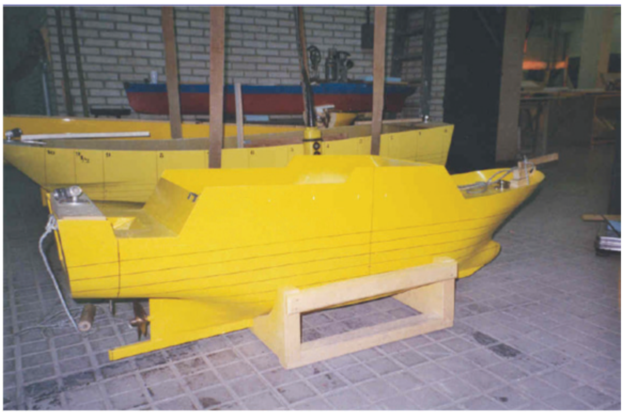

Figure 2: The model used for the experiments

The main purpose of this experimental program was to determine, firstly, the region of dynamic instability in regular waves for the vessel, and, secondly, to investigate the quantitative changes of parametric rolling in these conditions with respect to wave amplitude. Beforehand, certain preliminary checks and measurements had to be carried out as described below.

Initially, inclination tests were conducted to calculate the transverse metacentric height of the vessel. After determination of the transverse metacentric height, free-decay tests have been used to determine roll damping characteristics of the vessel for different maximum roll amplitudes and advance speeds. In this work, these roll decay traces were processed to determine linear and quadratic roll damping coefficients following the energy method approach, described in [15]. Moreover, the numerical model can also account for non-potential roll damping expressed in an equivalent linearized form so that linearized roll damping coefficients were calculated from experimental linear and quadratic roll damping coefficients.

The transverse metacentric height and roll damping coefficients were also used for the determination of the damped natural roll period of the vessel. It therefore made it possible to verify that the damped natural roll period of the vessel is two times the incoming wave period, corresponding to the low-cycle resonant condition, that was proposed for the experiments. This condition has been previously established by [24] as a condition that leads to the occurrence of parametric rolling, and is in good agreement with simplified estimates of susceptibility of occurrence of parametric rolling presented in here.

Lpp [m]	29.0
B [m]	8.0
Block Coeff.	0.437
BM_L [m]	29.65
BM_t [m]	2.203
Displacement [tons]	462.7
Draft at AP [m]	3.767
Draft at FP [m]	2.817
Draft at LCF [m]	3.369
GM_L [m]	27.90
GM_t [m]	0.33
KG [m]	3.92

Table 1: Main particulars of the vessel

After ascertaining these conditions, the parametric resonance tests in regular head waves were carried out. For the head sea tests, the trajectory of the model had to be constrained in such a way that the deviation from the required heading angle did not reach 10 degrees. This condition has been verified for the first few tests to make sure that it holds true. Finally, to stop the vessel from deviating from the course, it was decided to use two steel vertical mooring lines at the water level, fixing the heading of the vessel. As a result, the incoming wave angle was kept constant.

The incoming wave elevations and the motions of the vessel were recorded by the equipment in the towing tank and then passed onto a PC for further analysis. Different wave heights were considered using the same wave length to ship's length ratio to evaluate the effect of wave height (or wave steepness), and they will be discussed later in this paper. The detailing of this batch of tests can be found in Table 2. As outlined, wave frequency over natural frequency ratio is always kept at 2. The wave height was increased in steps of 0.5m, from 2 to 3 metres, delivering four experiments of 1, 1.25 and 1.5 meters of wave amplitude. Additionally, 1 meter of wave amplitude was tested in order to examine the effect of smaller waves on the vessel.

Exp.	T_w (s)	H_w (m)	ω_w / ω_n	L/L_{pp}
1	5.58	1.50	2.00	1.67
2	5.58	2.00	2.00	1.67
3	5.58	2.50	2.00	1.67
4	5.58	3.00	2.00	1.67

Table 2: Parametric rolling experiments

4. ANALYSIS OF THE EXPERIMENTAL RESULTS

This section presents both the experimental measurements and the numerical predictions of the fishing vessel parametric rolling for the analysis of the conducted experiments. The numerical method described above was applied to the fishing trawler travelling in the same regular head waves tested in the tank. As previously outlined, the analyses of the motions are carried by comparing the experimental time records from ETSIN to the results of the time-domain simulation program of [21]. As suggested by the test table, the dynamic response of the vessel to the changing wave steepness will be examined more closely in this section.

The numerical code creates no transient stages for the incoming waves. The waves start directly at the crest that is defined by the wave amplitude. Therefore, all the experimental records also have been truncated to remove the transient stages of the incoming waves. It is important to make a direct comparison between the experiments and the simulations for the same initial values. However, the presented figures will show an initial roll angle for the experiments, defined as the angle of roll motion at the position where the expected wave amplitude reaches the vessel. Nevertheless, the initial pitch and heave for the numerical calculations are calculated using the response amplitude operators and phase angles, calculated by the strip theory frequency domain routine, and fed into the time domain program. This reflects the initial value problem, where an initial heave and pitch amplitude for the vessel, calculated using the corresponding position of the wave crest and the adequate wave amplitude should lead to more accurate results.

4.1 COMPARISON BETWEEN PREDICTIONS AND MEASURED ROLL AMPLITUDES IN STEEP WAVES

In Table 3 the results of the experiments and simulations are compared. The third column presents the experimental results and the fourth column presents the numerical predictions. The amplitudes of roll motion are 17.6 degrees, 27.5 degrees, 31.7 degrees and finally 33.6 degrees, increasing as the wave height increases. As for numerical predictions, unitary wave height does not predict parametric rolling. Higher wave amplitudes deliver decaying amplitudes of roll with increasing wave heights. However the roll motion at 2.5 metres of wave height is very precise. The decay behaviour is explained in detail later on. For the unit wave height, absence of numerical roll is also examined further.

In terms of experimental deviations, examining the wave records revealed that the wave heights were slightly higher than the targeted values at some parts of the time series. This is also confirmed in the experimental figures later presented. However, the results depend on the steady wave amplitude, and usually it was in good agreement with the targeted values. Overall, the agreement between the experiments and the numerical results differ depending on the wave heights tested. For 2.5 meters of wave height, the steady roll angle is very precisely predicted.

Exp.	H_w (m)	Experimental (°)	Numerical (°)
1	1.00	17.6	0.01
2	2.00	27.5	36.1
3	2.50	31.7	32.4
4	3.00	33.6	23.8

Table 3: Predictions and measurements of roll amplitudes under parametric rolling

Regarding the numerical roll amplitude decay behaviour in 2, 2.5 and 3 meter wave heights, it should be mentioned that similar results could also be identified in the works of [25, 26, 27, 28]. In fact, [26] have attributed this behaviour to the existence of a non-linear stiffness term that is proportional to the wave amplitude squared. Increasing the wave amplitude to a certain threshold the non-linear stiffness term overcomes the parametric excitation terms that feed the energy required for the motion to be maintained. This condition could also be found in the published experimental data by [29], where a fishing vessel similar to this one had been tested in the tank. In more recent experimental investigations, with participation of this numerical model [30], the decay of the roll amplitude could be also experimentally confirmed for the ITTC-A1 containership.

In order to understand this 'artificial' decay of the roll amplitude, along with the wave amplitudes, it is also important to assess the coupled heave-roll-pitch motions effect on parametric rolling responses in detail, by checking their time records. Namely, it is important to compare the measured amplitudes in these three modes against numerical predictions so that the reason why the predictions deviate from measurements may be identified. With that in mind, all the experimental time series have been analysed and show the same feature regarding strong coupling between roll and pitch motions, which therefore resulted on different roll responses experimentally. To illustrate this feature, experiment 5, corresponding to 2.5 metres of wave height is presented in Figures 3 and 4. Figure 3 presents the numerical predictions while Figure 4 represents the experimental measurements.

In this case it was experimentally confirmed that this fishing trawler at zero speed encountering regular head waves of about 1.67 times her own length, an amplitude of 1.25 metres, and a frequency twice her natural roll frequency will experience a low-cycle wave-induced parametric rolling situation, where a maximum roll amplitude of 32º is easily attained.

The direct comparison of Figures 3 and 4 also reveals that the roll motion fully develops to its steady amplitude at around 170 seconds in both cases. The experimental wave amplitude does not deviate too much from the intended 1.25 metres. While heave motion was not measured and is not available experimentally, a comparison of the periods of pitch with the period of roll confirms this condition as low-cycle parametric rolling. Pitch amplitude is generally well predicted at 5º, however, it can be noticed that alternate variations of positive and negative peaks of pitch motion (well in phase with consecutive positive and negative roll peaks) have been measured and predicted to be different by the numerical model. As this comparison shows, the numerical code delivers results close to experiments in this case. Still, the differences caused by the coupling effects can be discussed further in detail along with the results in unit wave amplitude.

4.2 DYNAMIC INSTABILITY IN LONGITUDINAL WAVES

Firstly, it must be noted that for a specific loading condition, low cycle parametric rolling occurs when the natural period of roll is equal to approximately twice the wave encounter period, the wave length is on the order of the ship length (between 0.8 and 2 times Lpp), the wave height exceeds a critical level, and the roll damping is low. For this fishing vessel, the requirements for low cycle parametric rolling in head waves to occur lead to a wavelength of 46.4 metres and a ship's roll natural period of 5.5 seconds, which then results in a wave frequency of 1.15 radians per second at zero forward speed. As shown in Figure 5, these operational conditions also fall into a Mathieu type zone of instability so that, in principle, critical wave-induced parametric rolling conditions could be easily identified prior to model tests. However, stability variations in waves are not so easy to address in such a complex dynamic condition such as parametric rolling in head waves.

With respect to stability variations in head waves, considering the righting arm variation with respect to the relative position of the fishing trawler in longitudinal waves. As shown in Figure 6, the righting arm decreases with the wave crest amidships and increases with the wave trough amidships, in comparison with the still water righting arm for one metre wave amplitude. However, it should be noticed that, as shown in Figures5 and 6, these could be calculated in respect to still water either based on vessel's upright position or on linearized values (up to a certain roll angle)for the linearization procedure defined by [20]. Hence, as can be observed in Figure 5, the linearization procedure leads to an operational condition that 'artificially' falls outside the Mathieu type zone of instability due to smaller linearized stability variations.

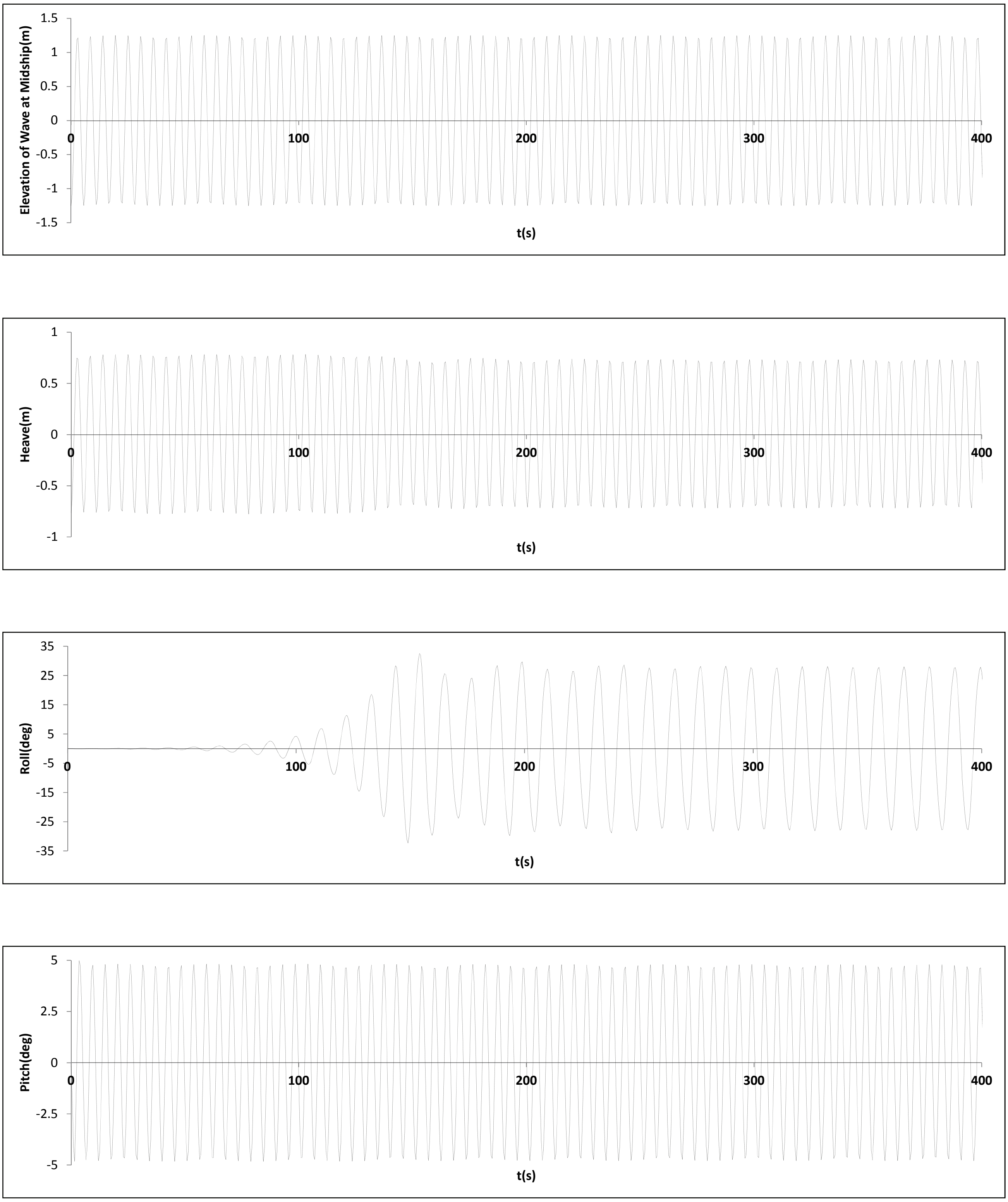

Figure 3: Numerical predictions of wave surface elevation, heave, roll and pitch motions for experiment number 5 at H_w = 2.5 metres, Wave Length / Ship's Length = 1.67, Vessel speed = 0 knots

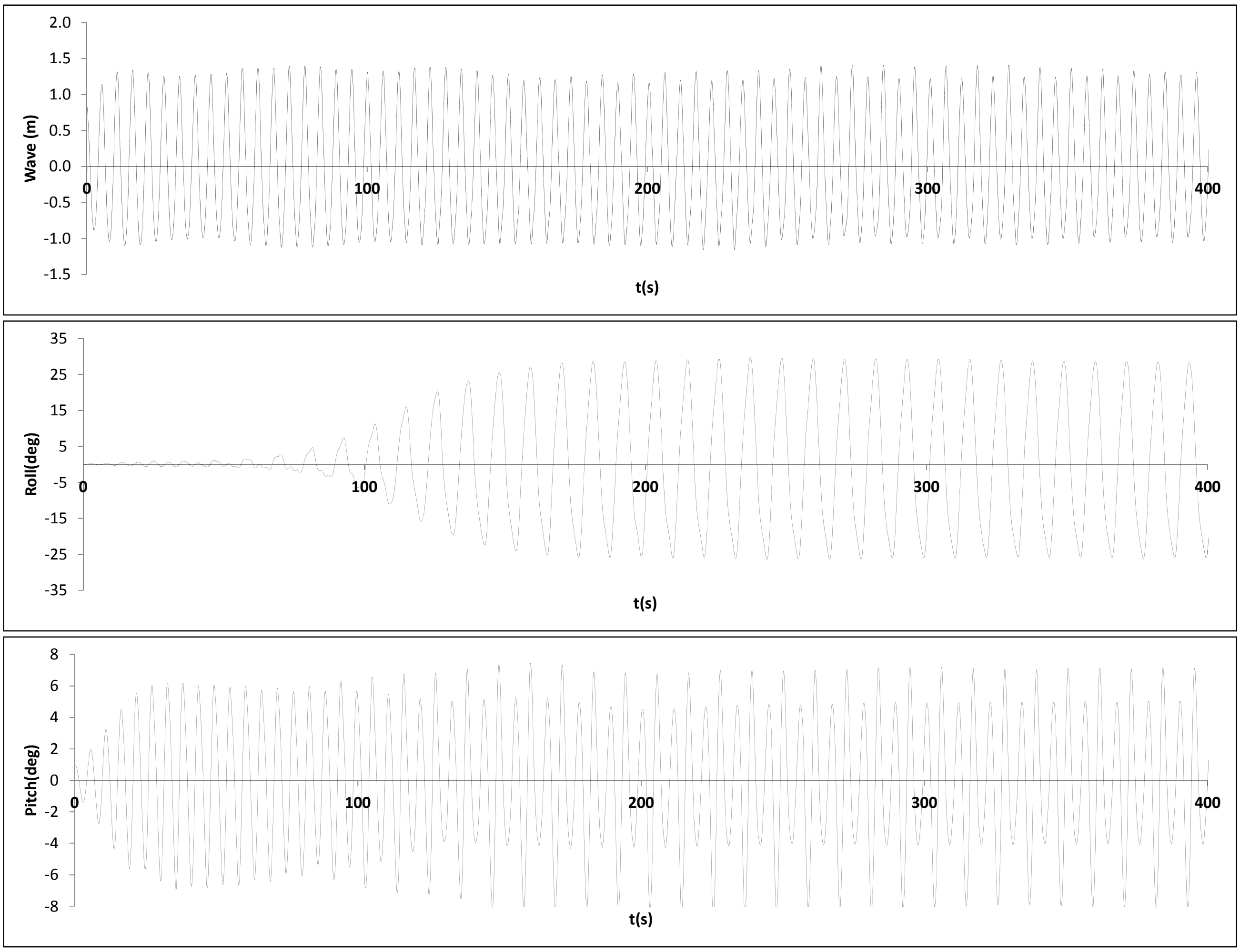

Figure 4: Experimental results of wave surface elevation, pitch and roll motions for experiment number 5 at H_w = 2.5 metres, Wave Length / Ship's Length = 1.67, Vessel speed = 0 knots. Heave motion was not measured experimentally.

This situation suggests that in smaller waves, the incurring time domain numerical stability variations are 'artificially' biased in dependence on the exciting wave amplitude, especially in the range below one metre wave amplitude. Therefore, it can be stated that at smaller waves, it is more difficult to deliver numerical comparisons due to the difficulties in modelling the hydrodynamic interaction problem between the ship and incoming waves. This is a condition that has to be taken into consideration when dealing with smaller vessels and smaller wave amplitudes, when assessing methods for the prediction of parametric rolling.

Focusing on these findings, there are at least two terms already well identified under parametric rolling conditions. The first is the effect of longitudinal and transverse coupled ship motions, heave-roll-pitch, and the second is the relative position of the hull with respect to the wave profile. The alternating pitch amplitude variations in phase with roll peaks shown in Figure 4 suggests that, apart from hydrostatic roll-pitch coupling, a third term probably associated with strong dynamic effects in waves, significantly affects coupled roll-pitch motions.

The next step would be to adopt this experimentally detected behaviour into the code to deliver better estimates of susceptibility and severity of low-cycle parametric rolling in regular head waves. Furthermore it would be of interest to researchers to obtain more experimental data which includes the heave, pitch and roll time series.

5. CONCLUSIONS

This paper has presented a study of the parametric rolling characteristics of a fishing trawler in regular head waves. In terms of severity analysis, the parametric rolling experimental measurements have been compared against the time domain numerical predictions for the same operational conditions. The experimental data collected also allowed susceptibility analysis of occurrence of parametric rolling based on two over-simplified parametric rolling models, whose results were presented on an Ince-Strutt diagram, Figure 5. It has been shown that, providing the low-cycle parametric resonance condition is attained and then it is largely possible to obtain roll angles equal to, or superior to 34º, both numerically and experimentally.

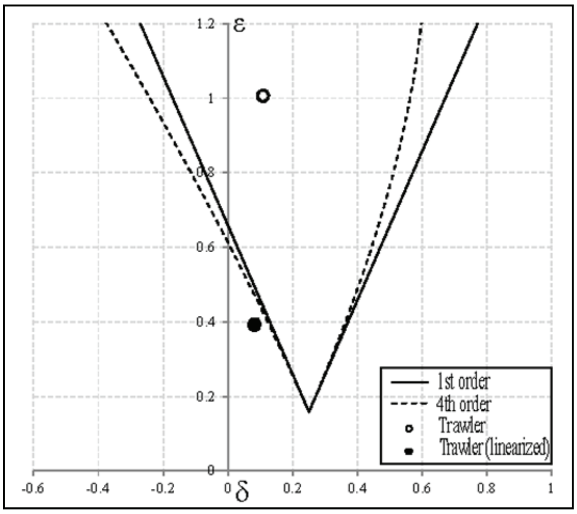

Figure 5: Ince-Strutt diagram for the vessel, showing instability zones for the trawler.

Numerical results reflect the effect of increased wave steepness as decay of maximum predicted roll amplitudes under parametric rolling in regular head waves. Results for this condition have been examined and detailed in the paper. A direct comparison of time series at the wave amplitude where the experiments and the numerical results match has revealed that pitch measurements show strong coupling effect between roll and pitch motions, experimentally. The complete motion of the vessel is significantly affected by the interaction between the modes and considering the experimental results presented in here, it will be important to incorporate these coupling effects into the numerical code. These so far ignored dynamic effects in head waves will have to be further investigated in the future by means of model testing with scaled models similar to the fishing trawler presented in this paper.

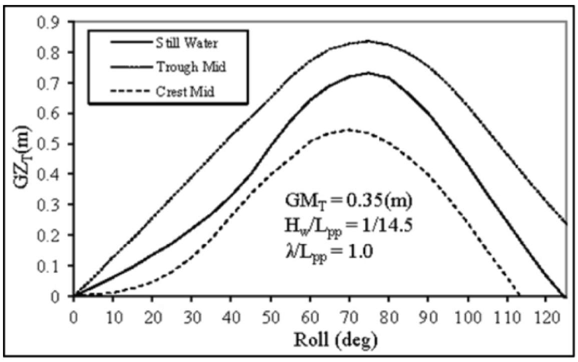

Figure 6: Righting arm curves of a fishing trawler in still water, in a 1 metre amplitude wave trough and in a 1 metre amplitude wave crest aligned with amidships.

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