# BENCHMARK STUDY ON NUMERICAL SIMULATION METHODS FOR THE PREDICTION OF PARAMETRIC ROLL OF SHIPS IN WAVES

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**ABSTRACT**

The main results and conclusions of an international benchmark study on the performance of computer simulation codes for the prediction of parametric rolling of ships in waves are presented in this paper. The benchmarked codes have been reviewed on a comparative way with respect to the specified benchmark tests and available experimental data. The study ship, a containership, was investigated in semi-captive condition of roll-heave-pitch and for a comprehensive set of sailing conditions in regular, group and irregular waves. The current capabilities of numerical simulation codes in predicting parametric resonance as well as the roll amplitude were assessed. The individual performance of the simulation codes proved divergent, whereas the current state of the art could be assessed on the basis of the best performing methods.

**Keywords:** *Benchmark, parametric roll, time domain simulation, intact stability*

## 1. INTRODUCTION

Time domain seakeeping codes may well reproduce the time varying restoring characteristics of the ships in waves hence they are employed for the prediction of the parametric rolling in waves. The codes are of diverse complexity and accuracy, and the relevant predictions are accordingly of diverse confidence. As the various simulation methods are not uniformly validated and their published data regard specific conditions, it is hard to assess their overall capacity, if not on the basis of benchmarks.

The benchmark study, presented in this paper, was conducted with the aim to record the currently employed numerical simulation methods for the prediction of parametric rolling and to assess the aggregate level of accuracy and efficiency of the numerical predictions. The study was organized within the E.C. research project SAFEDOR (SP.7.3.9, FP6) over the period June 2008-February 2009 and was coordinated by NTUA-SDL.

A number of independently developed computer simulation methods reviewed in this benchmark study and their predictions were evaluated comparatively as well as with available experimental data. So, the overall performance of numerical simulation methods could be assessed in a systematic and consistent way. The aggregate trends and general conclusions are herein of prime interest, whereas the particular performance of each individual method remains to be addressed by individual code developers.

## 2. PARTICIPATION IN THE STUDY

Qualified institutes that have been established as independent developers of relevant simulation computer programs were invited to participate in this benchmark.

Eventually thirteen (13) participants, as listed in the next Table 1, contributed numerical simulations to this study, which were produced with their own programs. Each participant has employed one simulation method, with exception of GL that used two different simulation methods and submitted two sets of results correspondingly. Hence, totally fourteen (14) simulation methods were reviewed.

According to the benchmark plan the identity of the simulation results was treated anonymously as the objective of the study was the assessment of the current overall performance of the software tools and not of individuals, while avoiding any commercial implications. Hence, in the next sections the results are presented with coded names 01-14, which do *not* correspond to the list of Table 1.

**Table 1.** Participation to the benchmark study.

| | |
|---|---|
| - LabOceano/COPPE, Federal University of Rio de Janeiro | Brazil |
| - Technical University of Denmark, Department of Mechanical Engineering | Denmark |
| - Helsinki University of Technology, Applied Mechanics Department, Marine Technology | Finland |
| - Germanischer Lloyd, Department Fluid Dynamics | Germany |
| - National Technical University of Athens, Ship Design Laboratory | Greece |
| - University of Trieste | Italy |
| - National Maritime Research Institute, Ship Structural Standards Research Group | Japan |
| - Osaka University, Dept. of Naval Architecture and Ocean Engineering | Japan |
| - Instituto Superior Tecnico, Technical University of Lisbon | Portugal |
| - Chalmers University of Technology, Shipping and Marine Technology | Sweden |
| - KTH Centre for Naval Architecture, Royal Institute of Technology | Sweden |
| - University of Southampton, School of Engineering Sciences | UK |
| - The Ship Stability Research Centre, Dept. of Naval Architecture & Marine Engineering, Universities of Glasgow and Strathclyde | UK |

## 3. BENCHMARK TESTS

The benchmark containership (section 6) was studied for a series of twenty two (22) conditions, as summarized in Table 2. The tests were defined by variation of

- Ship loading condition, $GM$, $I_{xx}$
- Ship speed, $Fn$
- Wave heading, $\beta$
- Wave height, $H$
- Wave periods, $T$
- Wave profile, *regular, group, irregular*

**Table 2.** Benchmark tests matrix.

| TEST | GM (m) | Fn | Wave Heading (deg) | Height, Period (m, sec) | Description |
|---|---|---|---|---|---|
| T01 | 1.38 | 0.00 | - | - | Roll decay (calm water) |
| T02 | » | 0.08 | 180 | 3.6, 10.63 | Regular (1 harmonic) |
| T03 | » | » | » | 5.7, 10.63 | » |
| T04 | » | 0.12 | » | 3.6, 10.63 | » |
| T05 | » | » | » | 5.7, 10.63 | » |
| T06 | » | » | » | 2.4, 10.63<br>2.4, 9.66<br>2.4, 11.55 | Group (3 harmonics) |
| T07 | » | » | » | 4.0, 10.63<br>1.0, 9.66<br>1.0, 11.55 | » |
| T08 | » | » | » | 5.0, 10.63 | Irregular (JONSWAP, γ=3.3) |
| T09 | » | » | 160 | 3.6, 10.63 | Regular (1 harmonic) |
| T10 | » | » | » | 5.7, 10.63 | » |
| T11 | » | » | » | 4.0, 10.63<br>1.0, 9.66<br>1.0, 11.55 | Group (3 harmonics) |
| T12 | 1.00 | 0.00 | - | - | Roll decay (in calm water) |
| T13 | » | 0.08 | 0 | 3.6, 8.00 | Regular (1 harmonic) |
| T14 | » | » | » | 6.0, 8.00 | » |
| T15 | » | 0.04 | » | 3.6, 8.00 | » |
| T16 | » | » | » | 6.0, 8.00 | » |
| T17 | » | » | » | 2.4, 8.00<br>2.4, 7.11<br>2.4, 8.89 | Group (3 harmonics) |
| T18 | » | 0.08 | » | » | » |
| T19 | » | » | » | 5.0, 8.00 | Irregular (JONSWAP, γ=3.3) |
| T20 | » | 0.08 | 180 | 5.0, 12.12 | Regular (1 harmonic) |
| T21 | » | 0.12 | » | 5.0, 12.12 | » |
| T22 | » | 0.08 | » | 4.0, 12.12<br>1.0, 10.77<br>1.0, 13.47 | Group (3 harmonics) |

In setting up the test matrix, due attention was devoted to include variations for all the parameters involved in the problem and that affect the sensitivity of the simulation methods; simultaneously the least uncertainties with respect to the environmental and ship sailing conditions were considered. Hence, the ship was assumed restrained (*semi-captive*) to move in 3 degrees of freedom (heave, roll and pitch), thus minimizing any uncertainties in speed and course keeping. Also, the majority of the tests were defined for deterministic waves, namely simple harmonic waves and tri-chromatic wave groups (Figure 1); also, two tests were considering irregular waves of specific spectral representations. The test matrix was complemented with two free roll decay tests in calm water.

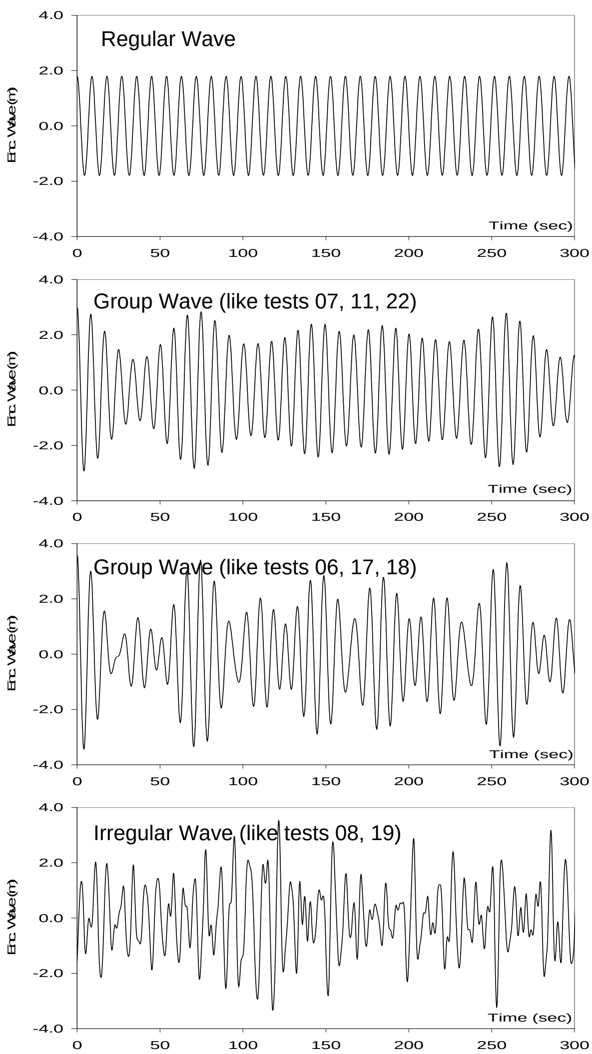


Figure 1. Profiles of encounter wave elevation.

The test matrix has been designed in such way that in some tests the ship does not experience parametric resonance, while in others a clear resonance occurs. As the actual roll response was not known to participants in advance, the roll resonance for each test was practically a possible event, however not certain. Thus, the prime focus of the study, the predictability of the roll resonance occurrence, could be evaluated. Furthermore the prediction capabilities for the roll motion amplitude under resonance could be evaluated too.

The above benchmark tests have been also physically conducted with two series of ship model experiments, (HYDRALAB, 2007 and SAFEDOR, 2008). The model experiments regard the same test conditions as in the benchmark, Table 2. The containership model was tested in semi-captive conditions too, namely moving only in heave, roll and pitch. Hence, the model could be towed at constant speeds and courses against the waves. Such measurements are suitable for the benchmarking as any uncertainties related to the speed and course could be kept suppressed.

## 4. STUDY DATA

The data of this study comprised of the ship hull definition, the ship loading conditions and two experimental measurements of roll and pitch in decay tests in calm water (corresponding to Test 01). No other data were available to the study participants. Hence, genuine prediction conditions were established as there was not any other information known to participants in advance regarding the behaviour of the investigated ship. Therefore, the collected set of predictions was unbiased and an adequate sample for the evaluation of the prediction capabilities of the simulation tools.

## 5. NUMERICAL SIMULATION METHODS

The fourteen (14) numerical simulation methods benchmarked were all non-linear time domain seakeeping methods. The ship hydrodynamics were modelled within the potential theory for the motion of ships in waves, either with a strip method (10 methods:

01, 02, 04, 06, 08, 09, 10, 11, 13, 14) or a panel method (four methods: 03, 05, 07, 12).

The simulation methods differ also with respect to the employed roll damping models, where linear roll damping was applied by five (5) methods (02, 05, 06, 13, 14) and non-linear, quadratic or cubic, applied by the other nine (9) methods. The parameters of these models were determined on the basis of the roll decay data, whereas one method (07) was based only on semi-empirical model. With respect to the roll restoring, only method (02) applied linear restoring, whereas the other methods applied non-linear modelling.

While the benchmark tests were defined for the ship motion in 3 degrees of freedom (roll, heave and pitch), some methods simulated partly a different number of degrees, which was considered appropriate by the participants or it was a practical constraint of the employed methods. In particular three methods (08, 12 and 14) simulated only one degree roll motion, method (09) simulated additionally the sway and surge, method (10) simulated additionally the sway, and finally method (13) simulated additionally the surge and yaw.

Not all the simulation methods could deal with all the wave profiles specified in the benchmark. Four methods (11, 12, 13 and 14) could only simulate regular waves (single harmonic). And method (08) could simulate the different wave profiles, but it was limited to longitudinal waves only (not oblique waves 160 deg).

## 6. THE CONTAINERSHIP STUDIED

The benchmark study refers to the containership ITTC-A1 (Table 3), which has been tested before in *free running* tests in Japan (ITTC 2005, Umeda et. al 2000).

The ship hydrostatics, as computed by the simulation methods, was found to be convergent, which indicates that practically all methods employed comparable geometric ship models and their predictions corresponded to the ship specified by the study.

**Table 3.** Main dimensions of the containership.

| *Item* | *Ship* |
|---|---|
| length : $L_{pp}$ | 150.0 m |
| breadth : *B* | 27.2 m |
| depth : *D* | 13.5 m |
| mean draught : *T* | 8.5 m |
| Trim: *t* | 0.0 m |

The computed *GM* as a function of *KG* is shown in Figure 2. Apparently the simulation methods converge with respect to *GM*, which is a crucial parameter for the roll resonance. The differences are bounded within 2.4% from the average, and only method (14) is singled out with a difference 6.1% (this method was also the only divergent method for the ship displacement by 3.5%).

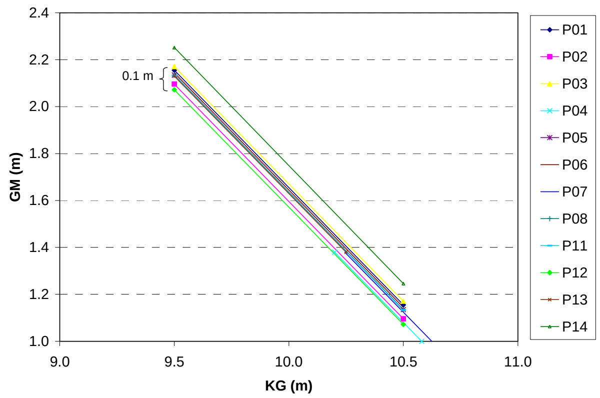


Figure 2.*GM* computed by simulation methods.

Figure  presents the GZ curves for the free to trim condition, and for the methods that submitted relevant data. The maximum difference curve presents the difference between the maximum and minimum *GZ* for each heel angle. The methods are assumed convergent up to a heel angle of 20 degrees, while over that heel they gradually diverge. This should be related to the applied geometrical modelling for the upper part of the ship (forecastle and poop deck, hatch covers), as the deck submergence occurs around 20 degrees. As the differences are practically limited at the range of large angles, and the benchmark tests regard roll motion below 20 degrees (with exception of test 16) the observed difference is assumed not practically affecting the benchmarking.

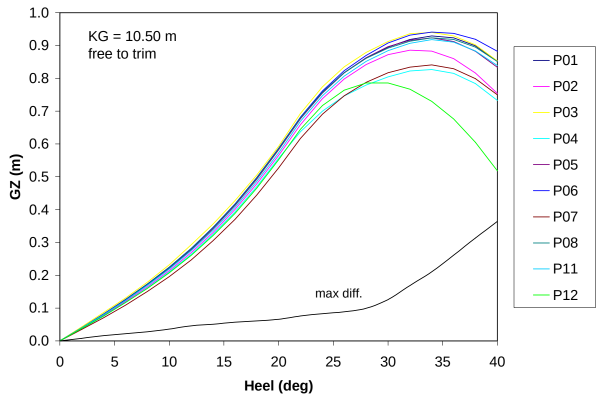


Figure 3. *GZ* curves in free trim condition.

## 7. ROLL DECAY TESTS

Two roll decay tests (Test 01 and Test 12) in calm water were simulated; they were used for the verification of the ship loading conditions as assumed in the numerical simulations as well as the damping models applied.

Both Figure 4 and Figure 5 present the simulated roll decay for Test 01. Two groups of simulations could be identified, namely those of Figure 4 where the experimental data have been used to tune the ship hydrodynamic inertia properties; and those of Figure 5, which seem to have not. Regarding the roll damping, methods (except method 07) have evaluated damping on the basis of the decay data.

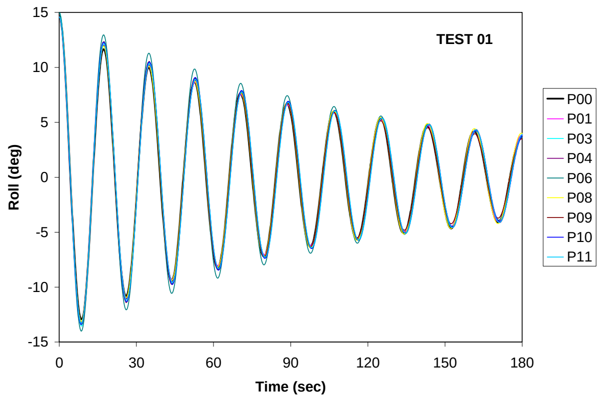


Figure 4. Roll decay. Methods tuned hydrodynamic inertia to the experimental data.

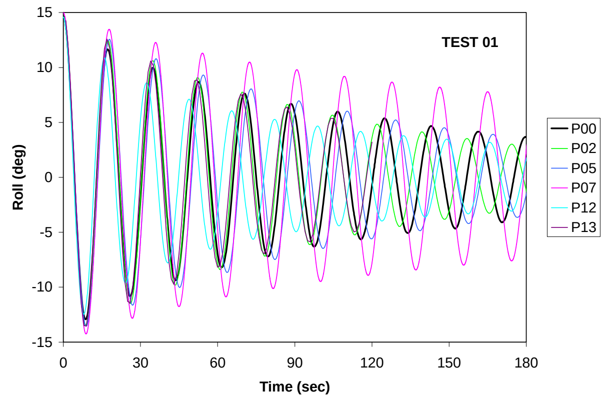


Figure 5.Roll decay. Methods without tuning of hydrodynamic inertia to the experimental data.

With the second roll decay Test 12 (*GM*=1.0 m) the effect of *GM* on natural roll period inertia and roll damping could be tested. All methods could consistently predict an increase of roll period with the decrease of *GM*, while they demonstrated divergent performance with respect to roll damping, e.g. for methods (02) and (08) the roll decay coefficient increased by +30%, while method 13 demonstrated a moderate decrease -15%.

## 8. ROLL MOTION SIMULATIONS

Figure 6 presents typical roll motion simulations as submitted to this study. The most frequent motion was that of *steady rolling* resulting after some transient period. The *non-rolling* response was also characteristic, where after some initial roll disturbance the roll motion eventually vanishes. Finally, *capsize* events were also encountered as presented.

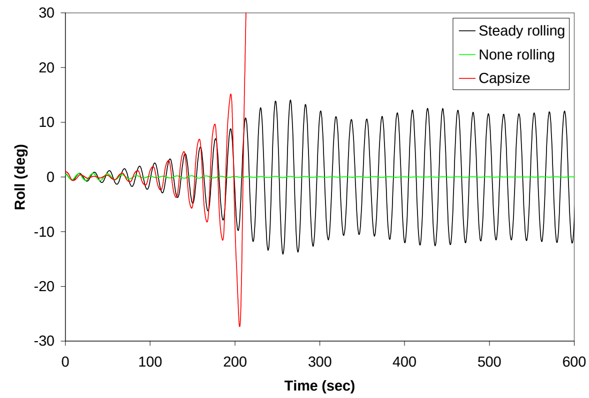


Figure 6. Typical roll motions simulated.

A total of 239 numerical simulations in waves (from 14 methods) were finally verified as compatible to the study and further considered for the performance assessment. Figure 7 samples the simulation results for the benchmark test 07, namely group head waves at Froude number 0.12. The simulated mean roll amplitude[1] is shown with the vertical bars, and its variation for the considered stationary roll response, is shown with the vertical error bars of width equal to the standard deviation of the roll amplitude. The corresponding experimental data are labelled as method 00.

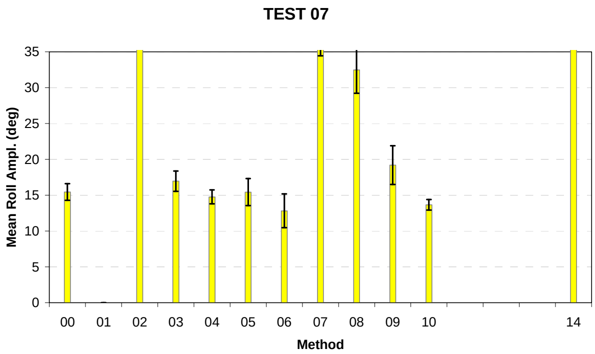


Figure 7. Simulated roll amplitude for test 07 (group-head waves).

For this test, only method 01 failed to predict the occurrence of the roll resonance. Methods (11, 12 and 13) have not submitted herein simulation results, hence they are not labelled. From the successful methods to predict resonance occurrence, six methods (03, 04, 05, 06, 09 and 10) have also successfully predicted the roll amplitude, whereas the other four methods (02, 07, 08 and 14) have predicted much larger amplitudes or even capsize.

## 9. PREDICTION OF ROLL RESONANCE

The overall performance of the benchmarked numerical simulations was defined as the weighted averaged performance of the individual methods. The weight function was defined with respect to the number of benchmark tests eventually simulated by each method.

The success rate for the prediction of the roll resonance inception for each method was uniformly evaluated as

$$\textit{Success rate}\ \ P = \frac{1}{n}\sum_{i=1}^{n} q_i \quad \text{for } n \text{ simulated tests}$$

Where the function $q_i$ is defined as $q_i = \begin{cases} 1 & \text{for } (x_i - x_{,cr})(\overline{x}_i - x_{,cr}) \geq 0 \\ 0 & \text{for } (x_i - x_{,cr})(\overline{x}_i - x_{,cr}) < 0 \end{cases}$ and formulates the successful prediction of the roll amplitude $x_i$ in comparison to the experimental amplitude $\overline{x}_i$ and a reference critical roll amplitude $x_{,cr}$. Namely, a successful prediction is recognized when both simulation method and model tests estimate a roll amplitude higher (or lower) the reference critical angle $x_{,cr}$.

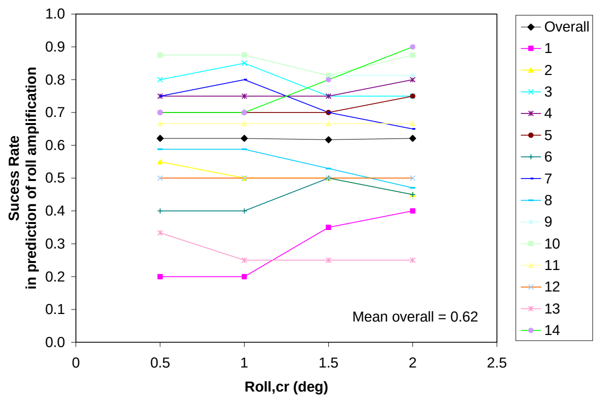


Figure 8. Prediction of the roll resonance inception.

Above Figure 8 summarizes the success rate of all the simulation methods for the prediction of the roll resonance inception, and for a reference critical angle up to 2 deg. The success rate of the individual methods is notably divergent ranging between 0.2 and 0.9. The overall mean rate is shown in the middle of this diagram. Unlike the individual simulation methods, the mean overall success rate demonstrates almost independence with respect to the taken critical angle, with a mean value of P=0.62. The observed convergence for the mean overall is a matter of the large sample used (239 predictions), whereas for each

[1] Mean value of consecutive roll amplitudes

individual method the less number of (20) predictions is herein not sufficient for convergent results.

Omitting the poorly performing methods, namely those with success rate less than the average, then the success rate of the best performing methods could be assessed too. With reference to the group of the eight (8) methods higher than the average, the mean rate is P=0.78. This result demonstrates the current capacity of best performing simulation tools, which could practically predict successfully in 8 out of the 10 cases the inception of parametric roll resonance.

## 10. PREDICTION OF ROLL AMPLITUDE

The capability of the methods in predicting the magnitude of the roll amplitude was evaluated too. For each individual method two statistical measures, namely that of the *correlation coefficient r* and the *standard deviation σ*, were used for comparison with the experimental data. Both combined, could provide a clear picture for the performance of each method as well as for the overall performance, as presented in Figure 9.

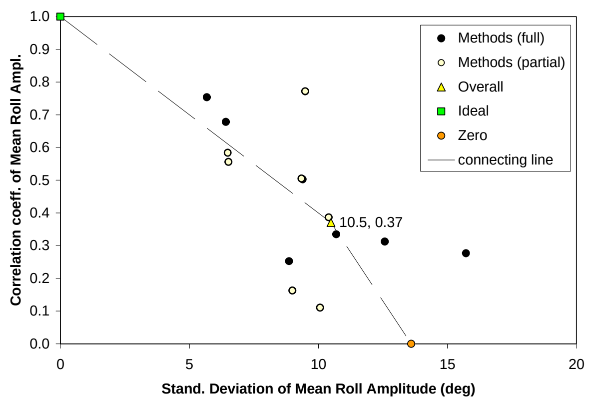


Figure 9.Performance of simulation methods to predict roll amplitude in parametric resonance.

In Figure 9 each individual method is shown with a full black symbol when all the benchmark tests have been simulated (20 tests) and with an empty symbol when the benchmark test matrix has been partially simulated (less than 20 tests). Obviously the partial methods contributed less to the overall assessment as it is determined by the weight function (section 0). This diagram is also complemented with the three discrete points, which are connected with a dashed line. The middle point (Overall) corresponds to the overall average performance of the 14 simulation methods, the top left (Ideal) and bottom (Zero[2]) points represent theoretically entirely successful simulations and entirely lack of predictability respectively.

A group of four (4) methods in the region of ($r$=0.7, $\sigma$=5.0) can be easily distinguished as the herein *best performing* methods. Also, one method of high correlation, but of large deviation in predicting the magnitude of roll amplitude (10 deg), can be observed at the top of the diagram. The deviation and correlation of the four best performing methods are ($\sigma$=6.4 deg, $r$=0.64). These values are almost twice as good as for the overall level ($\sigma$=10.5 deg, $r$=0.37), and they represent the current frontier of numerical simulation prediction, as could be identified with this benchmark.

## 11. DISCUSSION OF RESULTS

The prediction capabilities of benchmarked numerical simulation tools was assessed for the average overall level as well as for the best performing methods, representing the current frontier in the field. The assessment was based on the mean statistical performance of the methods in the specified benchmark tests, which was convergent and can be considered with confidence.

The recorded performance was weakly depended on the tested wave profiles. The simulation methods seem to perform comparably well for regular (P=0.61) and non-

[2] *Zero level* is assumed when the probability to predict roll resonance equals 0.5 and the non-zero roll amplitude is evenly distributed between 0 and 35 degrees.

regular (groups or irregular) wave conditions (P=0.65).

The two different sources of experimental data used (two different tank facilities), do not affected the results, and in both cases P=0.62. Concurrently, as the experimental data correspond to different *GM*, it seems that the change of *GM* has not affected the capabilities (performance) of the methods.

A remarkable dependence of the performance is that of the employed 3D or strip method hydrodynamics. Four methods (03, 05, 07 and 12) that applied 3D hydrodynamics seem to better reproduce the resonance conditions as they resulted to a mean success rate P=0.74, whereas the other methods a mean rate P=0.57.

Furthermore, an improved performance was recorded for the methods that had tuned the hydrodynamic inertia of the ship with respect to the experimental roll decay data. The tuned methods (of Figure 4) resulted to a success rate P=0.65, against P=0.54 for the other methods (of Figure 5).

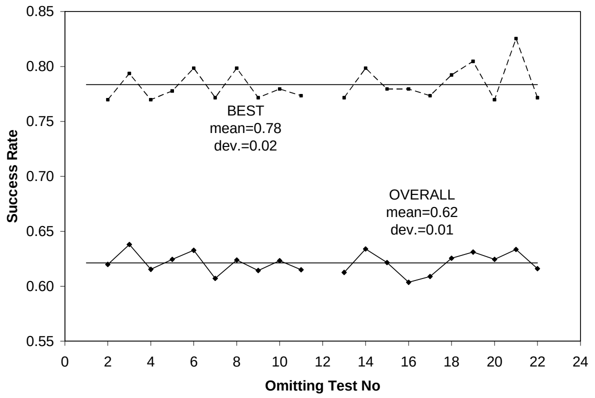


Figure 10. Impact of each benchmark test on the success rate.

The impact of each benchmark test on the predictions can be observed in Figure 10. There the success rate has been evaluated on the basis of 19 benchmark tests (instead of 20), each time omitting one test (note that Tests 01 and 12 are decay tests). Both the overall and the best rate (of Figure 8) are herein plotted, and a standard deviation 1% and 2% respectively results.

In Figure 11 the aggregate success rate of all the simulation methods and for each benchmark test is presented, which provides insight the possible effects of the recorded performance. According to this diagram, the simulation methods seem to achieve the highest performance of P=0.90 in quite different kind of tests 07, 16 and 17, which correspond to group-head waves (test 07), regular-stern waves (test 16) and group-stern waves (test17). The lowest performance is identified for the tests 03, 11 and 14, which correspond to regular-head wave (test 03), group-bow waves (test 11) and regular-stern waves (test14). Hence, some general performance trend could not be detected on the basis of these tests.

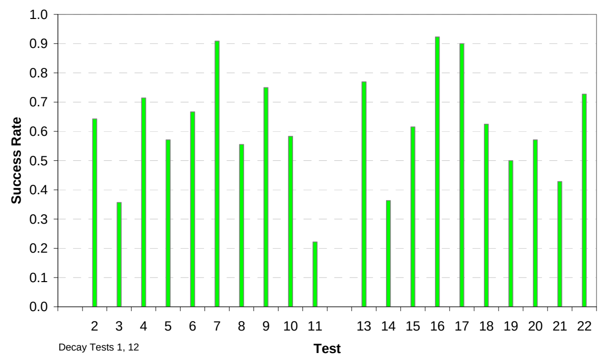


Figure 11. Aggregate prediction of the roll resonance for each benchmark test.

However, a close up to the tests 03 and 14 (which are in larger wave height compared to tests 02 and 13 respectively) reveals that the effect of the wave height was hard to be reproduced by the simulation methods, as most of the methods predicted opposite trend compared to the experimental data (detailed discussion by Spanos and Papanikolaou, 2009).

Test 11 proved the most demanding test: it comprised the complex conditions of non-regular (tri-chromatic group) wave in oblique heading (160 deg). Only nine (9) methods simulated this test, which seems to be on the limit of capabilities of currently employed simulation tools.

## 12. CONCLUSIONS

A benchmark study on the performance of computer simulation software tools for the prediction of parametric rolling of ships in waves has been conducted with a very good international participation, namely thirteen participants worldwide and fourteen different methods; it enabled representative conclusions for the current capabilities.

A notable divergence in the performance of individual tools has been recorded, ranging from poor performance and up to those of higher efficiency. As a consequence, the overall efficiency of the benchmarked tools appears low.

Nevertheless, the current prediction capabilities were determined on the basis of the group of the best performing simulation tools. On this basis, the mean probability to successfully detect the inception of the parametric roll resonance was estimated to be 0.78, while the predictions for the amplitude of roll motion deviated on average 6.4 deg. The corresponding figures for the overall benchmarked tools were 0.62 and 10.5 deg respectively.

The analysis of the above results has shown that major weaknesses of the methods are related to the large amplitude wave hydrodynamics, as well as to the complex wave profiles like that of oblique-group waves. The benchmark could also detect some advantage for the tools that applied 3D hydrodynamics.

Finally, considering the variety of simulation models reviewed in this study, some further development of the employed models appears necessary in order to further improve the best performance currently achieved.

## 13. ACKNOWLEDGEMENTS

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