VALIDATION METHODOLOGY FOR SIMULATION SOFTWARE OF SHIP BEHAVIOUR IN EXTREME SEAS

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ABSTRACT

The paper presents a methodology for validation of a computer software for simulation of ship motions and capsizing in extreme waves. The requirements for dedicated model experiments are defined and the validation phases of the software are explained. Examples of the validation of certain parts of the computer program as well as the whole software package are included.

Keywords: *ship extreme motions, simulation software, software validation, capsizing simulations*

1. INTRODUCTION

Ship motions in waves can be predicted by use of computer programs, either in frequency or time domain, called generally seakeeping programs. Contemporary programs provide quite good quality of predictions for large ships in moderate to high sea states. Validity of predictions is limited to steady state of motions.

However, in extreme waves, the dynamic behaviour of a small or mid-size ship far exceeds a typical range of motions considered in predictions of ship seakeeping in moderate seas. The amplitudes of motions are very large, the deck is frequently flooded or its part deeply immersed in surrounding water, and various transient physical phenomena occur, which may dramatically change the character of typical ship motions predicted by a standard seakeeping software, and may lead to capsizing. This can be predicted realistically only by simulations in time-domain.

The time-domain simulation software has to contain appropriate modules representing not only large, non-linear motions of the ship but also all the significant transient phenomena which affect ship behaviour in reality and may bring the ship to capsizing. The software has to have a capacity to simulate full capsizing process, and has to be thoroughly validated, if it is considered as a tool for the judgement of ship capability to survive in extreme seas.

Mathematical description of certain transient phenomena is a challenging task and the theoretical models of individual phenomena have to be validated. Validity of the final software package has to be thoroughly verified. The problem lies in the fact that capsizing process is a transient event which depends strongly on initial conditions and on the inter-dependence of the component transient events. To validate such a process, a set of dedicated model tests have to be carried out. The experiments should provide the basis for the comparison not only the final motion of the ship but also the hydrodynamic forces acting on the hull. The additional forces imposed by deck-in-water effects, water sloshing on deck and other phenomena, which are present during the capsizing process have to be examined as well.

The computed time histories have to be compared with relevant experimental data, both in terms of instantaneous magnitude and the phase, in time domain. The validation process should be performed in a specific order so that all significant elements of the computation algorithm could be validated step by step, up to verification of the final result of the simulation.

2. METHODOLOGY FOR SYSTEMATIC EXAMINATION OF A PROGRAM FOR SIMULATION OF SHIP BEHAVIOR IN EXTREME WAVES

The logical chain of the main elements in the validation process of a simulation software for extreme ship motions is presented in Fig.1.

The validation procedure starts with the examination if the ship form, ship mass distribution, and other dynamics features essential to ship behaviour, are appropriately represented in the computer program.

The way in which extreme waves are represented in the computation algorithm, have to be carefully validated against the wave time-records and spatial distribution, if available. Close representation of wave profile is essential in the validation process.

Typical way of seakeeping software validation is represented by the perimeter loop on the diagram (Fig1): "ship form / waves → forces on the hull → motion simulation → comparison of predicted motions with the results of free running model tests". In the steady state of motion this procedure may be sufficient. In case of motions in extreme waves, however, the final outcome of waves action depends strongly on initial conditions at the moment of wave impact, on the interrelation between modes of motion, and on various transient phenomena which may or may not occur in the dynamic process of motion. A good agreement in comparison of predicted motions with experimental results in one case does not necessarily mean that the software predicts correctly. In another case, the result might be completely opposite. This is particularly true in case of capsizing predictions.

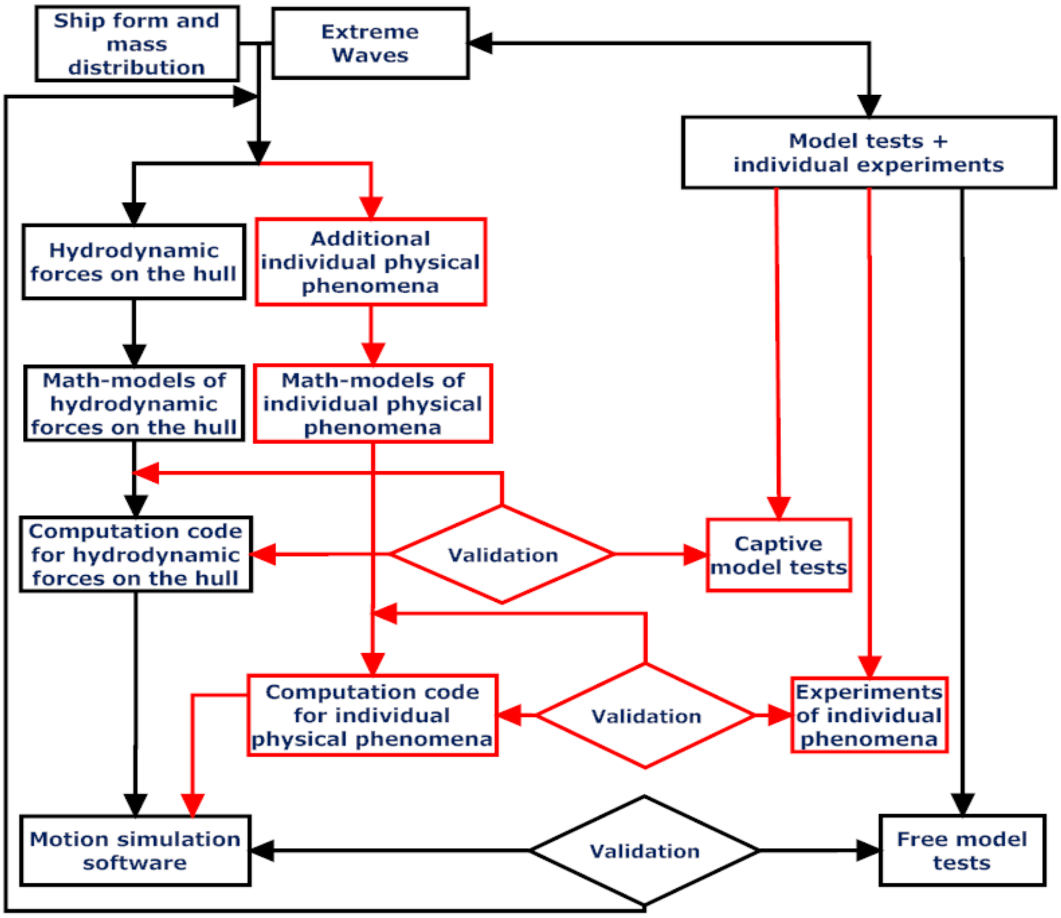

Figure 1. Main elements in the validation process of a software simulating ship behaviour in waves.

To assure that the program predicts correctly the motions, the modules computing all the hydrodynamic forces during motion in extreme waves have to be validated directly against forces measured in dedicated experiments. Correct and full representation of the hydrodynamic forces in the computing scheme is fundamental for the correctness of the predicted motion results. Hence, specially designed captive model tests, which will provide values of the hydrodynamic forces acting on the hull, have to be carried out. This procedure is shown in Fig.1 as the first level of validation:“computation code for hydrodynamic forces on the hull ← validation → captive model tests”.

Various transient physical phenomena, which may be generated during ship motion in extreme waves (e.g. deck-in-water, water on deck, etc.) usually change the ship motion in a dramatic way. They have to be modelled mathematically and incorporated to the main simulation code. Mathematical models of the individual physical phenomena have to be validated first, before incorporation to the main code. This can be done by comparison of the computation results with the results of specially designed experiments, representing the individual physical phenomena. This procedure is presented in the diagram 1 as the second level of validation: “computation code for individual phenomena ← validation → experiments of individual phenomena”.

Once the program subroutines calculating the forces on the hull and the individual physical phenomena have been validated and corrected, the final validation of the software can be performed. The theoretically simulated motions can now be compared with the corresponding results of free running model tests. The validation should contain comparison of relevant time histories of all motion components, including comparison of phases of the motions. If both, the time histories of the motions and their phases are in agreement with the experiment records, the simulation software can be considered as a correct representation of the real behaviour of the ship in extreme waves.

3. REQUIREMENTS TO MODEL TESTING

The validation procedure outlined in the previous chapter imposes specific requirements to the model testing. The concept of comparing forces and motions includes not only time histories of instantaneous values of the quantity considered, but also the phase of it. In order to provide such a possibility, the model tests have to make identification of an instantaneous wave crest position with respect to the model hull, possible. The following examples show how that requirement can be satisfied.

3.1. Captive Model Tests

Validation of the mathematical models of the hydrodynamic forces acting on the hull can be done by comparison of the computed forces and the corresponding measured forces in specifically designed captive model tests.

3.1.1. Fully captive tests

In the fully captive tests the model is rigidly fixed to the carriage through a six-component balance. The model can be fixed at various heel angles, and can be moved by the carriage with different forward speeds and required heading angles. An example of the fully captive test arrangement is presented in Fig.2.

Figure 2. Fully captive model tests in waves (Grochowalski, 1989).

The forces and moments measured by the balance are continuously recorded. The undisturbed wave is measured at a known distance to obtain the wave characteristics. In addition, the recording of water oscillations at both sides of the model provides possibility of estimating the wave deformation caused by model presence in the wave.

Full validation of the computed hydrodynamic forces on the hull requires identification of the instantaneous position of the wave crest with respect to the model hull in both, computation and experiment cases. This will enable to synchronize the computed and experimental time histories and to compare not just the amplitudes, but also the phases, which is essential for validation of the numerical models. In the model tests, the identification of the wave crest position can be achieved by video-recording of the tests. The time base of video-recording has to be synchronized with the main data acquisition system. If the video time-counter is continuously displayed on the screen and recorded during the experiment, analysis of the frozen frames of the video records gives excellent possibility to identify the wave crest position relative to the hull at any time of the process recorded. An example presented in Fig.2. shows the frozen picture from a fully captive test. Thanks to the marks on the hull, the position of the wave crest can be easily identified.

Fig.3. presents time-histories of all the hydrodynamic forces and moments measured in a captive test. The position of the wave crest, identified by the described way, is marked by the vertical lines for selected points along the model hull. Now the computation of the hydrodynamic forces can start for any selected position of the wave, and the resulting time histories of the forces can be compared directly with the measured ones.

Fully captive tests provide well defined conditions for the validation of the hydrodynamic forces exerted on the hull by waves, if they are not too large relative to the model. However, the total restraint causes large disturbance in the acting waves, and the forces measured in extremely steep, large waves may be unrealistic. In such cases, partly captive tests may prove to be more useful.

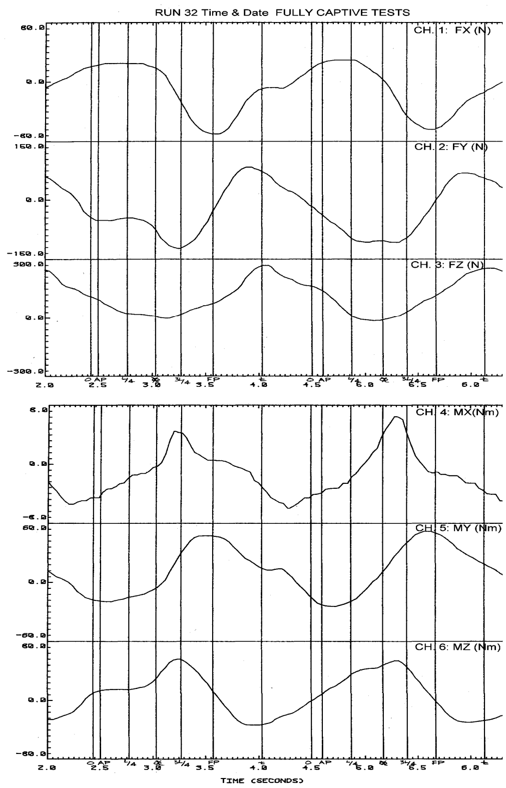

Figure 3. Example record of forces and moments measured in fully captive tests.

3.1.2. Partly captive tests

In the partly captive tests, the model is free to heave and pitch and restrained in the other modes. Such setup allows the model to react to the wave action and to maintain its constant displacement. The forces measured in the captive modes are more realistic and comparable to those in free running tests.

The model can be mounted at various heel angles and is moved by the carriage with required speeds and heading angles with respect to wave direction. The picture in Fig.4 illustrates partly captive testing. Similarly to the fully captive test technique, the video recording and data acquisition systems are synchronized. The heave and pitch motions are recorded as well as the forces and moments in the captive modes.

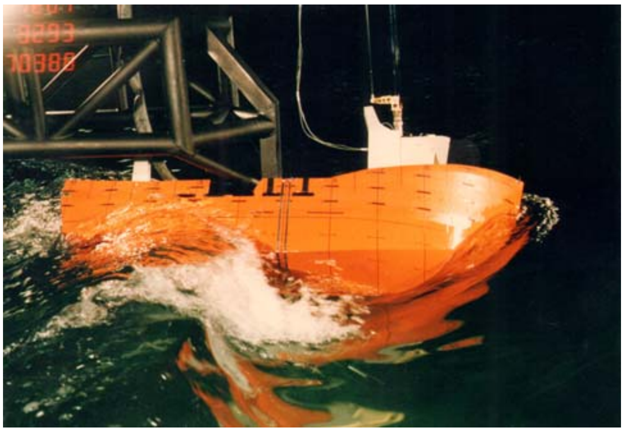

Figure 4. Partly captive model tests in waves. The model is free to heave and pitch (Grochowalski, 1989).

Applying the same analysis technique as in the case of fully captive tests, instantaneous position of the wave crest at the model can be identified. The example results of a partly captive test are presented in Fig.4.

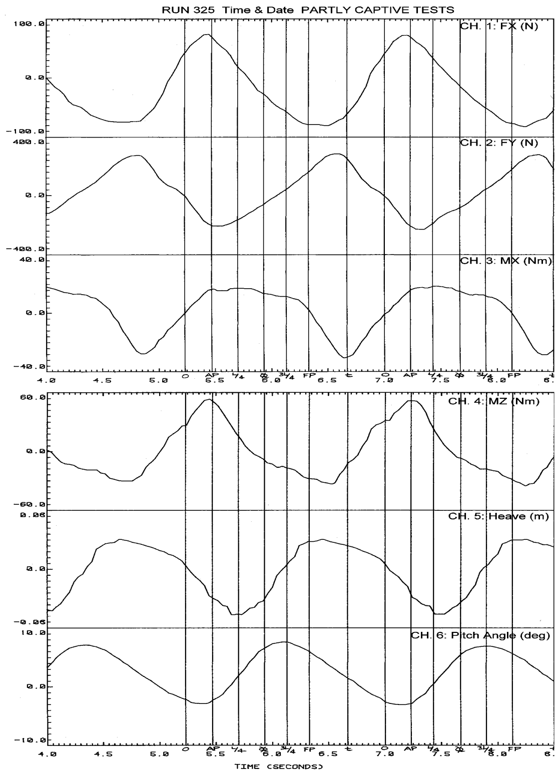

Figure 5. Example of recorded forces and moments in captive modes and free motions in heave and pitch.

3.2. Free-running Model Tests

The objective of free-running model tests is to measure and record the model behaviour in well defined and controlled wave conditions. The model must be free to move in all modes of motion in reaction to the wave action. For realistic modelling of a real ship behaviour, the model should be self-propelled and remotely controlled. Fig.6. presents an example of such free model tests.

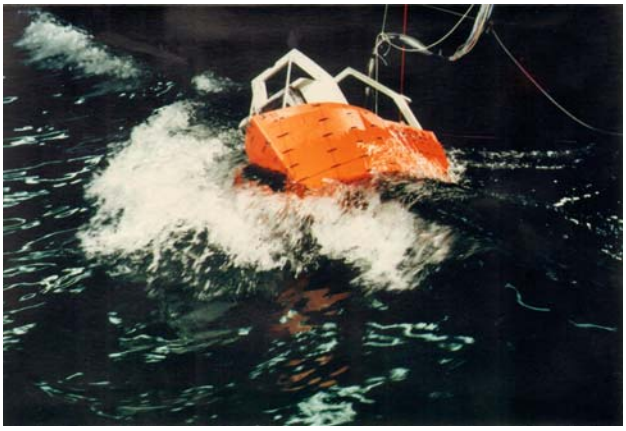

Figure 6. Free running model test in extreme waves (Grochowalski, 1989)

Similarly to captive tests, the time counter of the video recording should be synchronized with the time base of the data acquisition system to make the identification of the wave crest position possible. This is fundamental for the purpose of software validation. It allows to compare directly the time histories of motions computed with those recorded in the tests. Comparison of the instantaneous values of motion components and their phases for the same wave position in the simulation and in the tests, provides possibility of the ultimate judgement if the software calculates the motion correctly.

4. VALIDATION OF THE HYDRODYNAMIC FORCES ACTING ON THE HULL IN WAVES

This is the first essential element in the validation process. Without correct computation of the hydrodynamic forces exerted on the hull by waves, the motions predicted will not be correct. As mentioned before, only the direct comparison of time histories, obtained from captive tests and from numerical simulations, synchronized for assumed wave crest position, can provide reliable basis for the judgement whether the computing code is correct or not. The experimental technique of captive tests described in Chpt.3 provides the data needed to perform such a validation.

The simulation program has to have options to display the total hydrodynamic forces acting on the hull as one of the program outputs. In addition, possibility of monitoring all the components of the total forces (like: Froude-Krilov, radiation, diffraction, etc) allow to analyse all the elements of the mathematical models.

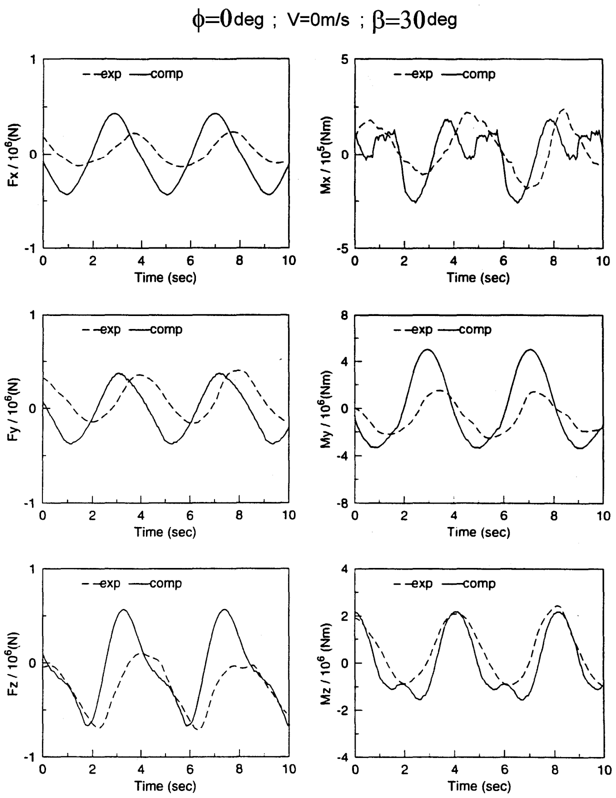

Figure 8. Comparison of the measured and computed hydrodynamic forces in a fully captive test (Huang et al.,1997).

In the total forces measured in the fully captive tests, the radiation forces are eliminated as the model is rigidly fixed to the carriage. This gives opportunity to validate the computation of Froude-Krilov and diffraction forces. The comparison of the total measured forces in a fully captive test with the corresponding computed by the program presented in (Grochowalski et al, 1998), is presented in Fig.8. The results show a good agreement (considering extreme steepness and the large size of the wave in comparison with the model size) except for heave and pitch. In order to find out the reason for such discrepancy, detail examination of the components of the total heave and pitch forces should be made. From the video records it was found, that there was some amount of water on the model deck. That was the reason for the discrepancy.

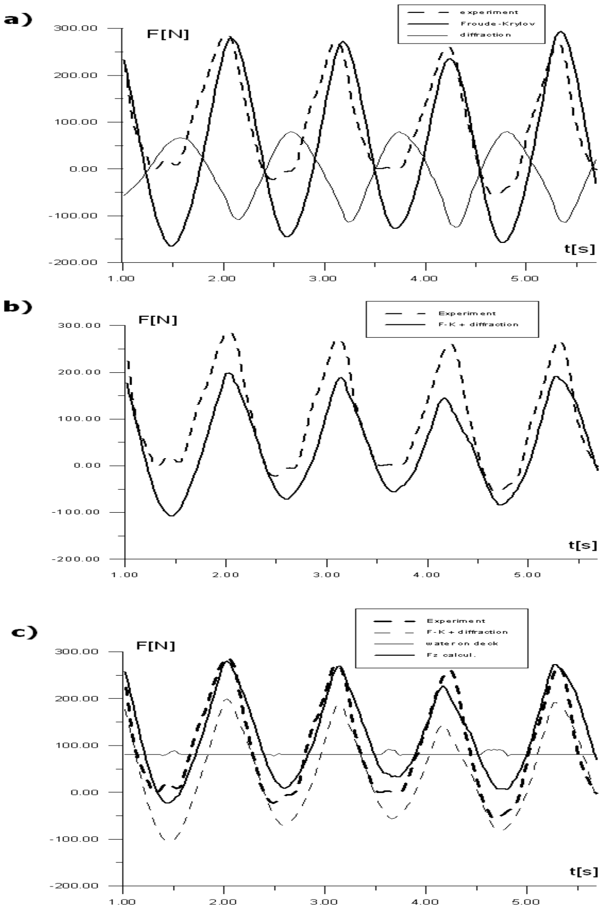

Figure 9. Comparison of the computed components with forces measured in the fully captive test.

An example of further detail analysis of this case is presented in Fig.9, which presents validation of a new code for simulation of ship behaviour in extreme seas, which is under development at the Polish Register of Shipping (Jankowski, 2007). The part a) shows comparison of F-K with the total force measured in the fully captive tests. Diffraction force is also shown. Part b) shows comparison of the measured total force with the total computed (i.e. F-K + Diffraction). The computed force is oscillating nonsymmetrically around zero, while the experimental is shifted up. When assessed mass of water on deck was included in the computation, the two total forces are in relatively good agreement. What is important, the phase in both cases is in excellent agreement.

The forces measured in the captive modes are closer to those acting when a ship moves freely. However, in order to compare the computed forces for the captive modes with the measured ones, the recorded time histories of free motions (heave and pitch) must be inserted into the computation module which assumes the instantaneous position of the hull in the wave profile. Only then, the forces in the captive modes can be compared.

5. EXPERIMENTS OF INDIVIDUAL PHYSICAL PHENOMENA

Occurrence of various physical phenomena during extreme motions may change dramatically the motion process. The phenomena introduce additional hydrodynamic forces which have to be represented in the computation algorithm. Special dedicated experiments should be designed and performed in order to provide information needed for the formulation of the mathematical model of the phenomenon, and to provide data for the validation. Each significant phenomenon should be validated individually. Then, the theoretical formulae can be implemented into the main simulation code.

The major phenomena which affect strongly ship motions are: water sloshing on deck, and deck-in-water effects.

5.1. Water shipping on and flowing off the deck.

Effects of water on deck depend on three phenomena: water shipping on deck, water escaping off deck, and flow of the resultant instantaneous mass of water in the deck space. Each of these phenomena have to be described mathematically and validated by experiments. The experiments should be designed in such a way, that the main phenomenon occurs only and the recorded data are clear to interpret.

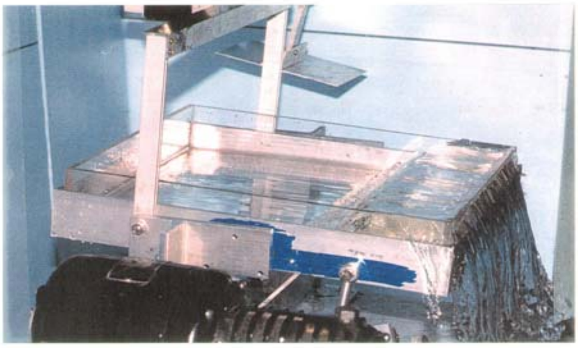

Fig. 4-2 Water Escaping off the Deck (Waterfall)

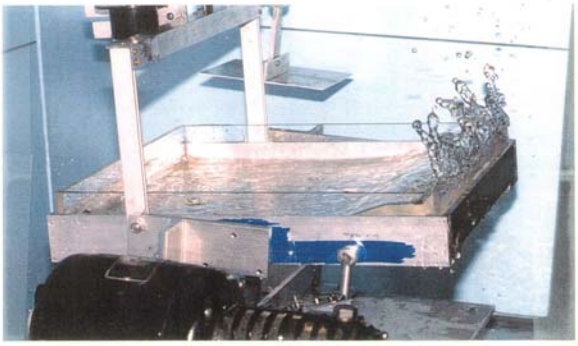

Fig. 4-3 Water Escaping off the Deck (Splash)

Figure 10. Experimental evaluation of mass of water escaping off deck. (Huang, et al., 1997).

Mathematical models allowing to compute the mass of water shipping on and the mass escaping off the deck have been presented in Grochowalski et al, 1998. Fig.10. provides illustration of the experimental validation of the math-model of water escaping off the deck. Validation of water shipping on deck was done using a simplified cylindrical model exposed to action of large waves in a tank. Once the resultant instantaneous mass of water is defined, the flow of trapped water can be simulated.

5.2. Flow of water trapped on deck

Validation of the theoretical model of water sloshing on deck could be done by use of the same experimental setup shown in Fig.10. Fig.11. presents comparison of computed and measured water surface profile during water flow in the deck well.

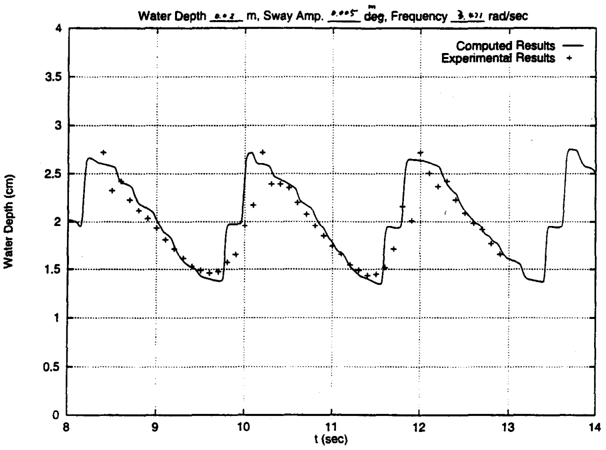

Figure 11. Comparison of the computed and experimental water surface profile in flowing on deck (Huang et al., 1997).

5.3. Deck-in-water effects

The hydrodynamic forces generated on the submerged part of the deck affect strongly ship motions, in particular the roll. They must be represented in the simulation program. A mathematical model of these forces has been developed (Grochowalski, 1993) and is partially validated. The experimental setup for investigation of the deck-in-water effects is shown in Fig.12.

Figure 12. Investigation of hydrodynamic forces on submerged part of deck (Grochowalski, 1997).

The applied test technique enabled to measure the force and pressure distribution on the deck only. Hence, direct comparison with the computed values is possible. The validation of deck-in-water forces is presented as a separate paper at the STAB 2009 Conference.

6. VALIDATION OF THE SIMULATION OF SHIP MOTIONS IN EXTREME WAVES

Once the validation of the modules which compute the hydrodynamic forces on the hull is done (first level of validation), and the forces generated by individual physical phenomena are verified (second level of the validation) and incorporated into the main computation code, the core of the simulation program can be considered as correct. The next step is to validate the prediction of the resulting motions. This has to be done by comparison of the time histories of simulated motions with those recorded in the free-running model tests.

In order to enable full validation, that is, to compare not only the magnitudes but also the phases, a special subroutine must be included in the simulation code to allow to use a piece of the recorded experiment results as the starting fragment of the simulation. This fragment, representing usually a half of a wave period, provides data necessary for calculation of instantaneous values of all the initial conditions in the simulation. This includes instantaneous motions, velocities, accelerations, and allows to calculate the memory effects. If the inserted experimental fragment starts at a time-point at which the wave crest position relative to the hull is known, the synchronization of the computation and experiment is full and complete. The software has “learned” the instantaneous values of the experiment time histories and can continue the simulation further down independently. At certain time point, the simulation is “released” and continues with its standard procedure. This approach has been developed for the purpose of validation of the simulation program based on theoretical background presented by Grochowalski, et al, 1998, and by Huang, et al, 1997.

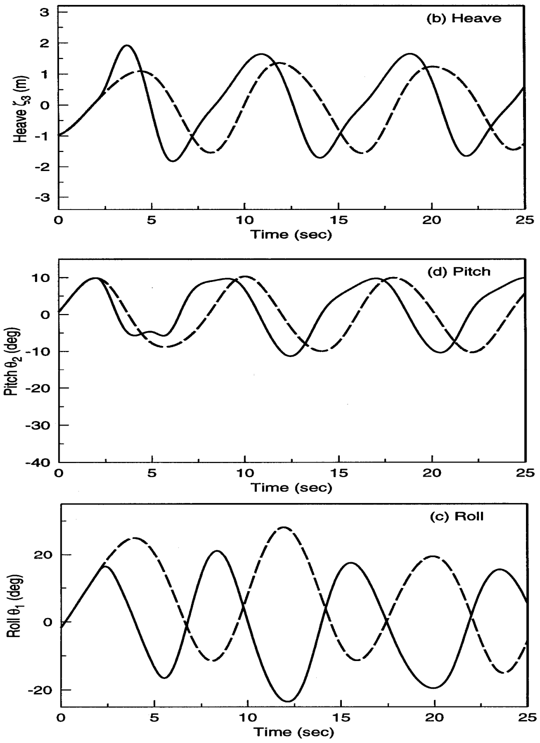

Figure 13. Initial part of simulation with the test results as the starting base for the computation.

An example of the use of this method is given in Fig.13. Three motions are presented for the illustration purpose. It can be seen that after the simulation was "released" (at 2.5 sec), the pitch simulation provided results which followed the experimental time history. The predicted heave and roll, however, do not follow the experiment results immediately after "release". They change right after that moment. Direction of the simulated roll motion changes rapidly to the opposite side, and the motion phase is shifted 180 degree. Although the predicted amplitudes are in excellent agreement, the shift in phases indicates that the software requires correction.

Another case is presented in Fig.14. Although the capsize event was predicted correctly, the remaining motion components were in opposite phase to those recorded. Here again, the motion amplitudes were predicted very well, yet the phases are not correct.

The method gives opportunity to detect all mistakes in the software, which could not be detected if comparison was limited to amplitudes comparison only. Fig.15. shows the comparison of the computed and measured results when the evident mistakes and inaccuracies were corrected. The evident problem with the simulation of course-keeping in extreme waves has to be treated separately.

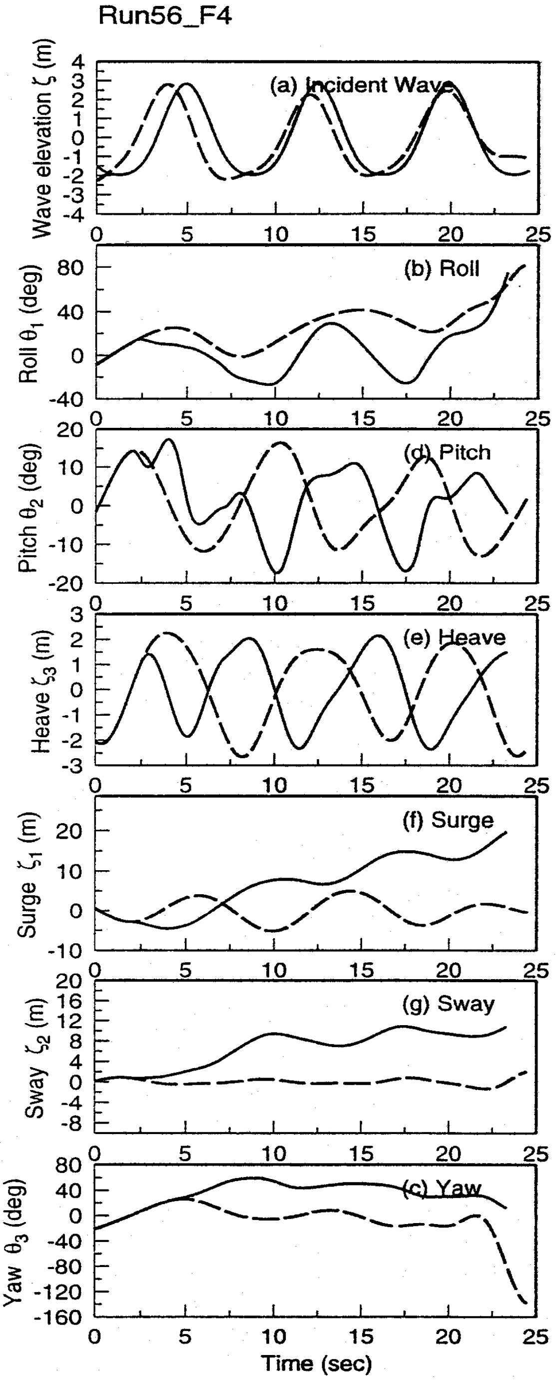

Figure 14. Comparison of all motion components for a capsize case (Grochowalski, et al, 1998).

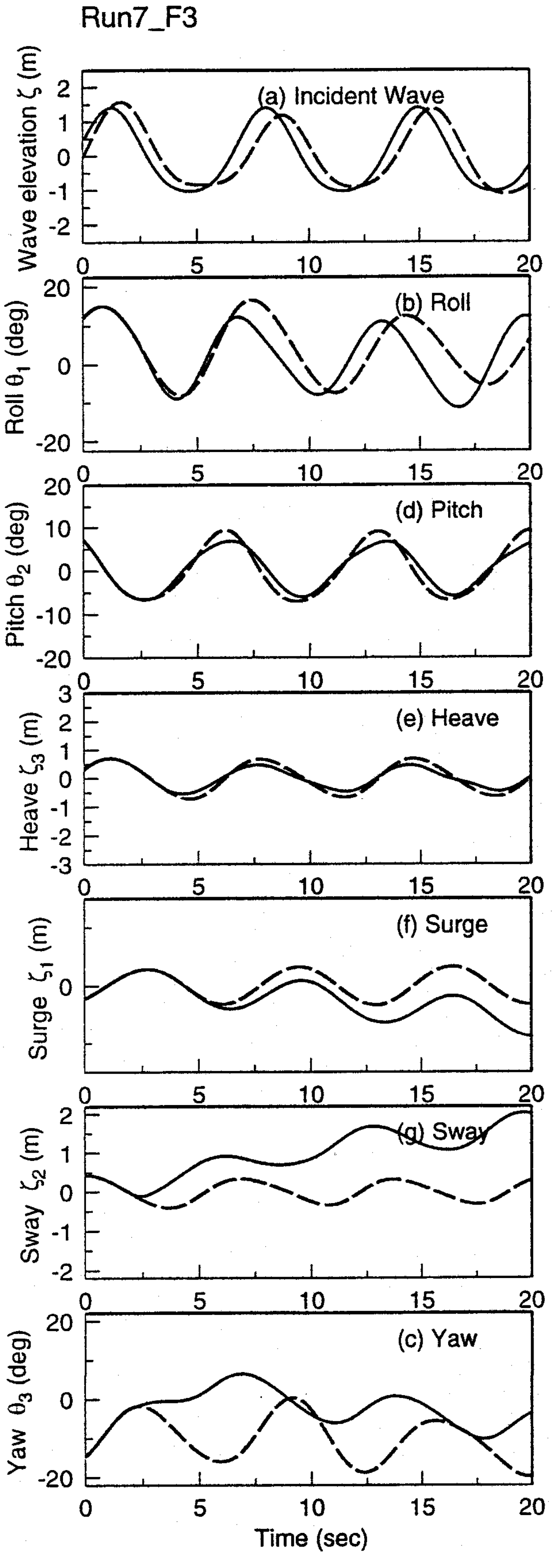

Figure 15. Comparison of all motion components for free model test and the simulation.

7. CONCLUSIONS

Ship behaviour in extreme seas is a very complex process. Large amplitude motions are accompanied by various physical phenomena which may make the ship behaviour unsteady. Transient phenomena can lead the ship to capsizing. The ability of predicting ship behaviour in extreme waves is of utmost importance for evaluation of the capsize safety margin. This cannot be achieved by use of traditional seakeeping software. The software for prediction of ship capsizing has to include all the significant elements of extreme behaviour, including the deck - external water interactions. Such a simulation program is very complex and all its major modules must be thoroughly validated.

The methodology of validation presented in this paper can be summarized as follows:

- Validation process should be based on the comparison of time histories of the results obtained by simulation versus relevant experimental results. Comparison includes both, amplitudes and phases.
- To make the comparison possible, the video recording must be synchronised with the main data acquisition system, which registers the time histories in the model tests. Such procedure enables to identify fully the instantaneous position of the hull with respect to the wave profile.
- Three levels of validation has to be performed: hydrodynamic forces on the hull, individual physical phenomena, and the final ship motion.
- Validation of the computed hydrodynamic forces on the hull is fundamental for the correctness of the whole simulation program. This goal can be achieved by comparison of time histories of computed forces with the results of appropriately designed captive model tests.
- Individual physical phenomena, generated during ship motions in extreme seas and affecting the ship behaviour, must be

validated separately by special dedicated experiments. Once their math-models are proved to be adequate, they should be incorporated into the main computation algorithm.

- After the first two levels of validation are performed and the results are satisfactory, the comparison of time histories of motions (both, amplitudes and phases) can be carried out. This is an ultimate validation of the simulation software.
- Comparison of the motion time histories obtained in the simulations with the corresponding experimental ones should start at a well defined position of the model in the wave profile. All the initial conditions required in the simulation must be then found from the experimental record of the motions. The method, which enables this, is presented in the paper.

When all the previous examinations provide satisfactory results, the time-domain simulation program can be considered as a reliable tool for prediction of ship behaviour in extreme seas, including capsize prediction. Now, it can be used as a tool for analysis of ship behaviour in extreme seas and a tool for development of stability safety criteria and standards.

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