Modelling Extreme Wave Sequences for the Hydrodynamic Analysis of Ships and Offshore Structures

Günther F. Clauss, Janou Hennig, Christian E. Schmittner
Technische Universität Berlin
Berlin, Germany

Abstract

For the analysis of non-linear processes such as large rolling and capsizing of ships as well for the evaluation of forces and motion behavior of offshore structures in extreme sea states, experimental investigations are still indispensable, both for the validation of numerical simulation tools and for basic insights into the underlying mechanism. Especially in ship design numerical simulation tools have improved significantly and are already considered routinely within the design process but are still under development and require further experimental confirmation.

One decisive point in such experimental investigations is the generation of deterministic wave sequences tailored for the individual test. This requires modelling of the non-linear wave propagation in order to know the wave evolution in space and time which allows the analysis of the non-linear process as a cause-reaction chain.

In this paper methods of analyzing non-linear wave propagation are presented and compared to results of linear wave theory as well as to corresponding measurements from wave tank experiments. A discussion of various practical applications closes the paper.

Keywords

Non-linear wave propagation, deterministic wave trains, moving reference frame wave trains, RANSE/ VOF, numerical wave tank, wave generation, model tests, intact stability

Introduction

The experimental investigation of extreme wave/structure interaction scenarios puts high demands on wave generation and calculation. For the deterministic analysis of motions and forces of ships and offshore structures wave excitation denotes the beginning of a complex cause reaction chain. The problem gets complex when the structure which has to be analyzed is moving at constant or non-constant speed since measurements in a model tank cannot provide the wave train at the position of the investigated model or in the moving reference frame of a cruising ship.

This paper recommends the use of an approach taking into account both analytical models and empirical terms for modelling non-linear wave propagation. This modified non-linear method uses linear wave theory as a backbone for non-linear wave description and is developed at each time step. The main advantage of the proposed method is the representation, synthesis, and generation of an arbitrary wave train at any position in time and space. Thus, standard model seas as well as special wave scenarios can be realized deterministically in a model tank and transformed either to other stationary positions or to the moving reference frame of a cruising ship.

The above wave generation technique is used as a validation tool for two numerical wave tanks. The first numerical wave tank uses a time stepping method based on potential theory. The simulation procedure calculates the free surface elevation and potential field of the entire fluid domain from which the pressure, velocity, and acceleration fields can be derived. The second method is a commercial RANSE solver which solves the conservation equations for mass and momentum. For capturing the free surface the volume of fluid (VOF) approach is applied. As a consequence, breaking phenomena can be considered.

A comparison with measurements discloses the advantages and disadvantages of each method.

The modified non-linear approach is applied to generate the "New Year Wave" which has been measured in the North Sea in the wave tank. With this rogue wave sequence the motions and forces of a semisubmersible are investigated experimentally.

The second application presented here addresses the experimental investigation of intact stability. The roll motion of a RoRo vessel due to deterministic wave trains is given in the moving reference frame. The test result is used for the practical design of ships by validating numerical tools for the evaluation of capsizing risk.

Modified non-linear theory for modelling wave propagation

The modified non-linear approach combines empirical and analytical wave models to allow a fast and precise prediction of non-linear wave propagation. It can be applied both to "forward" (downstream) and "backward" (upstream) prediction of wave trains. The "forward" prediction at arbitrary positions of the model tank (similar to the below presented numerical wave tanks) includes the representation of wave trains in the moving reference frame of a cruising vessel. The "backward" calculation is used for the transformation of given target wave trains to the location of the wave maker: This is a unique feature of the proposed procedure.

The method starts with a linear wave train $\zeta_0(t)$, either measured close to the wave maker or known from calculating the control signal of the wave maker. Thus, as a first step the wave train is checked with regard to linearity $\frac{H}{L_0} < 0.05$ over the entire wave length range. As a further step in pre-processing the wave train is written as Fourier series and time mapped with respect to the Shannon theorem:

$$\zeta_0(t_i) = \sum_{j=0}^{n/2} A_j \cos(\omega_j t_i + \varphi_{0j}), i = 0, 1, \dots n-1 \quad (1)$$

where

$$A_j = |F_j| \triangle\omega = \triangle\omega \left| \sum_{i_0=0}^{n_0} \zeta_0(t_{i0}) e^{-i\omega_j t_{i0}} \triangle t \right|, \quad (2)$$
$$j = 0, 1, \dots n_0/2$$

is the Fourier spectrum of $\zeta_0(t)$ with $\triangle\omega = \frac{2\pi}{n\triangle t}, \omega_j = j\triangle\omega$, and $i_0 = 0 \dots n_0$ denotes the initial time mapping. The corresponding initial phase spectrum is also calculated by Fourier transform of the initial linear wave train:

$$\varphi_{0j} = \arctan\left(\frac{\Im(F_j)}{\Re(F_j)}\right), j = 0, 1, \dots n/2. \quad (3)$$

The Hilbert transform of a function f is defined as

$$H(f) := \mathrm{IFFT}\left(\sqrt{(\mathrm{FFT}(f))^2 + (\mathrm{FFT}(f) e^{i\pi/2})^2}\right) \quad (4)$$

where "(I)FFT" is the abbreviation of the (inverse) Fourier Transform (Eq. 2), calculated by the Fast

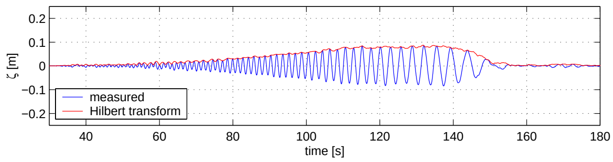

Fig. 1: Transient wave packet measured close to the wave board at $x = 8.82$ m: Linear wave theory is still acceptable for its description.

Fourier Transform algorithm. The inverse FFT gives:

$$\zeta(t_i) = \frac{1}{2\pi} \sum_{j=0}^{n/2} F_j e^{i\omega_j t_i} \triangle\omega, i = 0, 1, \dots n. \quad (5)$$

As a test case we chose a transient wave packet measured at two positions — the first location close to the wave board ($x = 8.82$ m) where the wave train is linear and the second position where the waves are already steeper and cannot be calculated by linear transform anymore ($x = 85.03$ m). Fig. 1 shows the linear wave train and its envelope.

According to Airy wave theory a wave train at an arbitrary position x_l is transformed to another position x_{l+k} by linear phase shift (the Fourier spectrum remains the same):

$$\zeta(t_i, x_{l+k}) = \frac{1}{2\pi} \sum_j F(\omega_j, x_l) e^{i(\omega_j t_i - k(x_{l+k} - x_l))} \triangle\omega. \quad (6)$$

Propagation of higher waves cannot be described by Airy theory since the propagation velocity increases with the instantaneous wave height. Also wave asymmetry and mass transport are introduced as considerable quantities. Fig. 2 shows the wave train from Fig. 1 transformed to $x = 85.03$ m by means of linear wave theory. Note that Airy theory is not adequate anymore. Especially, the higher frequencies deviate obviously since they propagate faster than predicted by linear wave theory. Also the shape does not correspond with the measured wave train (flat troughs, steep crests).

Our non-linear semi-analytical approach is based on Stokes III. It can be replaced by other terms from different theories as well.

Adapting Eq. 6, the phase C_{ij} is adjusted to the non-linear wave celerity c_{ij}. For each step l in space the following iteration scheme for the non-linear wave train has to be run:

$$C_{ij} = \varphi_{0j} - (\triangle x)_l k_{ij} \quad (7)$$

where φ_{0j} is the initial phase spectrum from Airy theory and C_{ij} is the modified phase calculated from

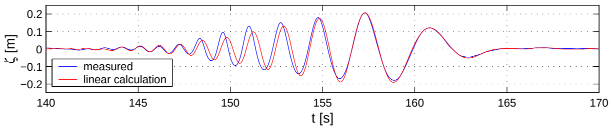

Fig. 2: Transient wave packet at $x = 85.03$ m: Comparison of registration with calculated data (linear transformation from $x = 8.82$ m — see Fig. 1) proves that linear wave theory gives inaccurate results.

the theory adequate to the investigated case. Here the following equations have to be solved to calculate the k_{ij} (see e. g. Kinsman (1965), Skjelbreia (1959)):

1. deep water $d/L_0 \geq 0.5$:
$$\omega_j^2 = g k_{ij}(1 + (k_{ij} a_i)^2) \tag{8}$$
(Stokes III) — solved by Cardan formulae

2. intermediate water depth $0.04 < d/L_0 < 0.5$:
$$\omega_j^2 = g k_{ij} \tanh(k_{ij} d)(1+(k_{ij} a_i)^2 \frac{\cosh(4 k_{ij} d) + 8}{8 \sinh^4(k_{ij} d)}) \tag{9}$$
(Stokes III) — solved by fix point iteration

3. shallow water $d/L_0 \leq 0.04$:
$$\omega_j^2 = g k_{ij} \tanh(k_{ij} d) \tag{10}$$
(linear wave theory)

Our test case is a transient wave packet measured at the Hamburg Ship Model Basin with a water depth of $d = 5.6$ m. Thus deep water limit frequency is $\omega = 2.34$ rad/s, the shallow water limit frequency $\omega = 0.44$ rad/s.

k_{ij} is subject to the temporary envelope $a_i = a(t_i) = H(\zeta_i)$. Thus the required Hilbert transform for the particular x_l is calculated at each time step t_i since it represents the instantaneous wave height at a particular point in time and space. It also considers the fact that the wave height increases on the way through the tank and non-linearities gain more and more influence. Fig. 3 gives an impression of the iteration of the k_{ij}.

In accordance with Stokes III wave theory the corresponding wave components at x_l are:

$$\zeta_{l,1}(t_i) = \sum_{j=0}^{n/2} A_j \cos(\omega_j t_i + C_{ij}), \tag{11}$$

$$\zeta_{l,2}(t_i) = \sum_{j=0}^{n/2} \frac{1}{2} a_i A_j \cos(2\omega_j t_i + 2C_{ij}), \tag{12}$$

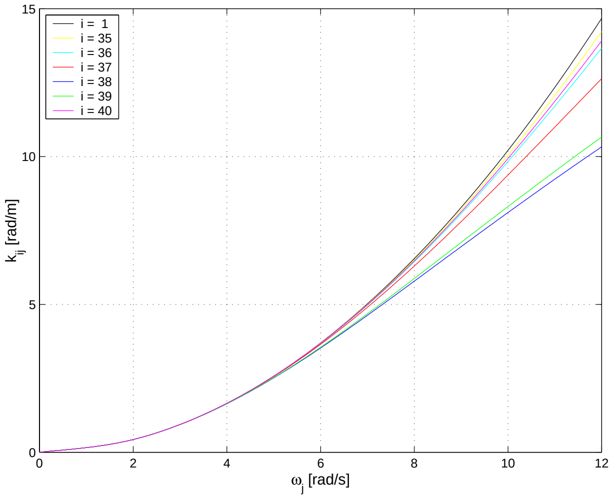

Fig. 3: Iteration of wave numbers $k_{ij}(\omega_j, a(t_i))$ as function of the instantaneous wave envelope a at time step t_i. Propagation velocity $c_{ij} = \omega_j / k_{ij}$ increases with "wave amplitude" a_i (see Eqs. 8-10).

$$\zeta_{l,3}(t_i) = \sum_{j=0}^{n/2} \frac{3}{8} a_i^2 A_j \cos(3\omega_j t_i + 3C_{ij}). \tag{13}$$

After summation of these components, $\zeta_l = \sum_{k=1}^{3} \zeta_{lk}$, the preliminary instantaneous wave train at the position x_l is given. Note that the phase velocity depends not only on frequency but also on wave elevation which is represented by the instantaneous envelope and its linear amplitude distribution. The correct shape is also composed of higher order components (bounded waves — Eq. 12 and 13).

The calculation of C_{ij}, Eq. 7-13, is repeated twice to average k_{ij} from the first and second step. The $(\triangle x)_l$ are chosen such that they decrease with increasing non-linearity. In our example the iteration is done with 2×105 steps in space and 1024 steps in time. Fig. 4 presents some iteration steps. The result of the calculation procedure is shown in Fig. 5 and compared to the measured wave train. Agreement with the measured time series is good. Compared to Fig. 2 the higher frequency terms show the adequate propagation speed and a pronounced non-linear shape with steep crests and flat troughs.

Wave generation for model tests

For model tests defined wave trains are generated in a model tank - preferable as deterministic wave groups at defined target locations which allows to correlate wave excitation to structural response. The wave generation process can be divided into four steps:

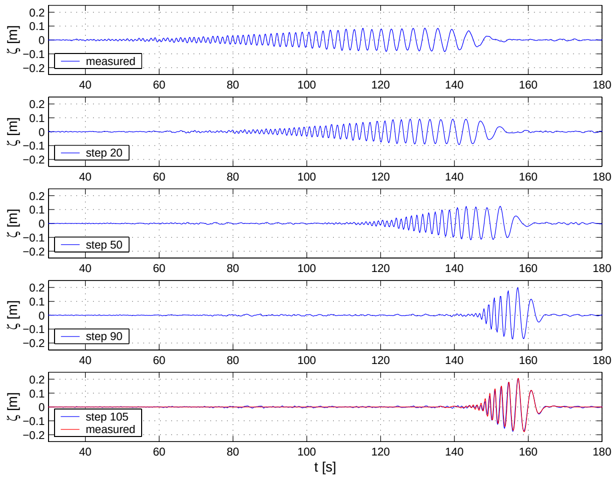

Fig. 4: Non-linear transformation of wave train in Fig. 1 to downstream positions (showing selected iteration steps): Comparison with measured data at $x = 85.03$ m is satisfactory (see also Fig. 5).

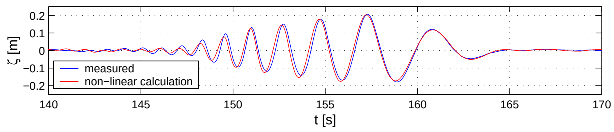

Fig. 5: Wave train from Fig. 1 is transformed to position $x = 85.03$ m using the described non-linear calculation procedure (iteration step 105) and compared to measurements.

1. definition of the target wave train
2. transformation of the target wave train to the position of the wave maker
3. calculation of wave maker control signal with regard to the characteristic RAOs of the wave maker
4. performance of model test

Definition of the target wave train

For the definition of an appropriate target wave train different methods are available. One procedure is to define target parameters like a typical "Three Sisters" wave sequence $H_s - 2H_s - H_s$ in terms of the significant wave height H_s (Wolfram et al. (2000)). An optimization routine is applied to get a target wave train satisfying the selected parameter set, see Clauss and Steinhagen (2000). A target wave is also defined by full scale measurements or as output of numerical simulations.

Transformation of the target wave to the wave maker

The second step in wave generation is the transformation of the given target wave train to the location of the wave maker. This makes use of the non-linear calculation scheme introduced above. Note that only the semi-empirical method allows the upstream calculation of a (non-linear) wave sequence from the target location back to the wave board.

Another approach to obtain the wave train at the wave board according to given target parameters is the combination of a numerical wave tank with an optimization method (Steinhagen (2001)).

Calculation of control signals

Knowing the wave train at the wave board it is easy to calculate the appropriate control signal(s) using the different characteristic transfer functions of the wave maker (Clauss and Hennig (2003)) which allows to generate the desired wave train for the model test at the target location.

Calculation of non-linear wave trains in the moving reference frame of cruising structures

For the deterministic analysis of motions and forces of ships and offshore structures the wave excitation denotes the beginning of a complex cause reaction chain. Dealing with a linear system the required time series are gained from frequency domain calculations. For a non-linear system, these models become inadequate, and more sophisticated methods have to be used. The problem gets even more complex when the structure is moving at constant or non-constant speed, as stationary measurements in a model tank do not provide the wave train at the position of the investigated model in the moving reference frame of a cruising ship. Wave probes can be installed at defined positions, but usually not at the position of the model (due to relative motions and disturbances). Especially when the ship is sailing at non-constant speed it is not a state of the art task to determine the wave excitation with regard to a moving reference point.

Therefore the measured wave train has to be transformed to a reference position of the model (both stationary and moving reference frame). The linear calculation scheme for moving models (wave in the moving reference frame of a ship) can be derived as follows:

$$\zeta(t_i, x_{l+k}(t_i)) = \frac{1}{2\pi} \sum_j F(\omega_j, x_l) e^{i(\omega_j t_i - k_j \triangle x_i)} \triangle\omega \quad (14)$$

where $\triangle x_i$ stands for the time varying distance between both locations. Considering the non-linear k_j and the adequate $F(\omega_j, x_l)$ from the empirical-analytical approach the wave train has to be calculated at the position of the model reference point $x(t_i)$ at each time step in order to get the non-linear moving reference frame wave train.

Deterministic wave trains

Applying the described non-linear approach all kinds of waves can be generated in a model tank:

- wave packets (Fig. 9)
- extreme waves such as "Three Sisters" (Figs. 7, 12)
- storm seas (Fig. 6)
- random seas with embedded high wave sequences (Figs. 8, 10, 11)
- regular waves with embedded high wave groups (Figs. 7, 12)
- realization of natural wave scenarios (Figs. 8, 11)

We call these wave trains "deterministic wave trains" and give examples of each of them in the following applications. The first application example is the validation of numerical wave tanks by modelling non-linear wave propagation. Two examples of numerical wave tanks are given here.

Validation of a numerical wave tank based on potential theory

The first numerical wave tank is based on a Finite Element Method discretization of the fluid domain. The two dimensional non-linear free surface flow problem is solved in time domain using potential theory: the fluid is inviscid and incompressible, and the flow is irrotational. Wave breaking is not considered. The atmospheric pressure above the free surface is constant and surface tension is neglected. Hence, the flow field can be described by a velocity potential which satisfies the Laplace equation. At each time step the velocity potential is calculated in the entire fluid domain, Clauss and Steinhagen (1999).

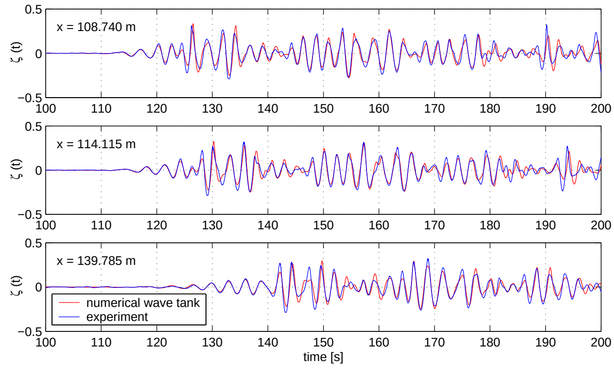

Fig. 6: Comparison of numerical (potential theory/ FEM) and experimental wave sequence generated by the same wave maker signal calculated by the modified non-linear theory (T_P = 14.6 s, H_s = 15.3 m): registrations at different positions.

To develop the solution in time domain the fourth-order Runge-Kutta formula is applied. At each time step a new boundary-fitted mesh is created. The procedure is repeated until the desired time step is reached, or the wave train becomes unstable and breaks. The numerical wave tank is able to simulate wave generators of piston type, single flap and double flap (and combinations). A complete description of this numerical wave tank is found in Steinhagen (2001).

Fig. 6 presents numerical results as well as experimental data generated by the modified non-linear approach to validate the numerical wave tank. The storm sea realization (T_P = 14.6 s, H_s = 15.3 m) has been modelled at the Hamburg Ship Model Basin (HSVA, length 300 m, width 18 m, water depth 5.6 m, equipped with a double flap wave generator) at a scale of 1:34.

Fig. 7 presents a superposition of a regular wave train with a wave packet. This tailored wave sequence is used for the investigation of large rolling and capsizing of ships, Clauss and Hennig (2003). As will be shown in Fig. 12 this irregular wave train turns out to become a rather regular wave with an integrated extreme wave if transformed to a moving reference frame.

Fig. 8 shows a simulation of the so-called New Year Wave. This rogue wave was reported from the jacket platform Draupner in the North Sea on January 1st, 1995, Haver (2000). The platform was hit by a giant wave with a wave height of 25.6 m (significant wave height H_s = 11.92 m) that caused severe damage. The wave is modelled in the wave tank at scale 1:81 (tank dimensions: length 80 m, width 4 m, water

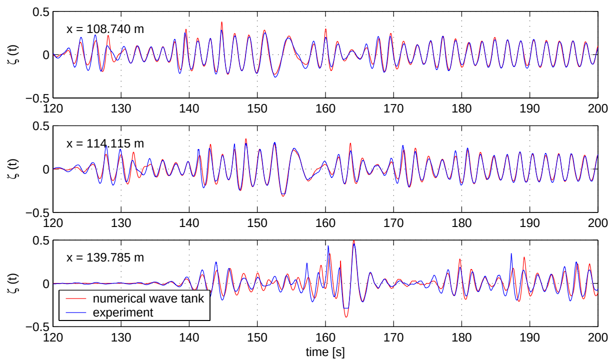

Fig. 7: Regular wave with wave packet for the investigation of large rolling and capsizing of ships (see Fig. 12). Numerical simulation based on potential theory/ FEM. Experimental data provided by the modified non-linear approach (scale 1:29).

depth 1.5 m, piston type wave generator).

Figs. 6-8 document the universality of the numerical wave tank for the calculation of wave evolution for different wave tanks with different water depth and types of wave generators. Like the modified non-linear theory the numerical wave tank predicts the non-linear evolution of wave trains and the wave/ wave interaction quite well. As the potential field is calculated at each time step, also velocity, acceleration and pressure fields are known. Only the modified non-linear theory is able to provide control signals both for generating deterministic wave trains in a model tank and as an input for the moving wall boundary of a numerical wave tank (Fig. 8). To overcome the limitations of wave breaking a numerical wave tank using a commercial computational fluid dynamics (CFD) solver is introduced in the next section.

Validation of a numerical wave tank based on a RANSE solver

The second numerical wave tank presented here is set up using the commercial state of the art CFD solver FLUENT (Fluent (2003)). For all flows, FLUENT solves the conservation equations for mass and momentum (Navier-Stokes equations). For simulating the free surface the Volume of Fluid method (VOF) is used which can deal with wave breaking phenomena. For simulating the wave board motion of the piston type wave generator a dynamic mesh approach (dynamic layering) is introduced. The motion of the wave board is simulated by moving the boundary forwards and backwards like the wave board in the ex-

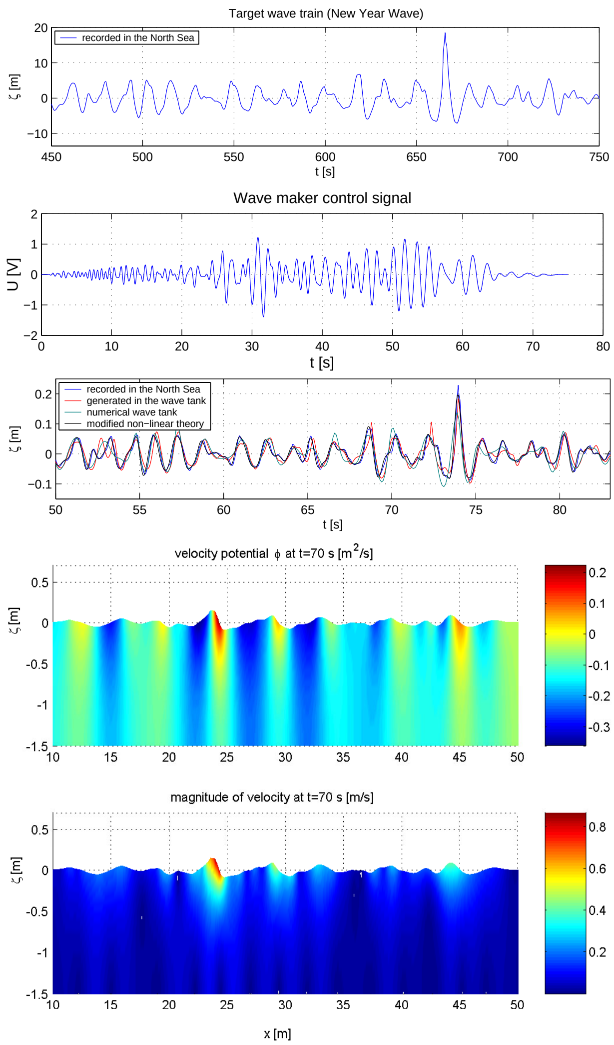

Fig. 8: Generation and analysis of the New Year Wave: applying the modified non-linear approach the target wave train (top) is transformed upstream to the position of the wave maker. The resulting control signal is shown here (second graph). Both the modified theory and the numerical wave tank based on potential theory are able to calculate the downstream wave train at the target position — the numerical tank only from the control signal which is provided by the modified theory. The corresponding wave field characteristics are provided by the numerical wave tank (scale 1:81).

periment. Therefore, cells have to be added to or deleted from the fluid domain as the size of the calculation domain changes with time. Further details on the numerical wave tank are given in Clauss et al. (2004a).

Fig. 9 presents the comparison between calculations

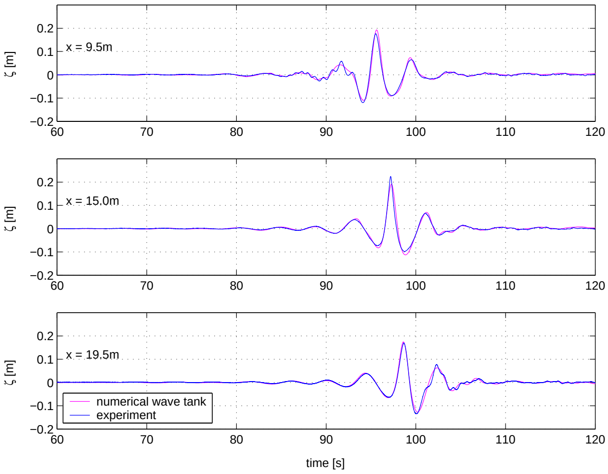

Fig. 9: Simulation of a wave packet ($H_{max} = 0.35$ m) based on RANSE/ VOF in comparison to measurement (same JONSWAP spectrum as in Fig. 10). Generation of the wave maker control signal for both model tank and numerical wave tank data using the modified theory.

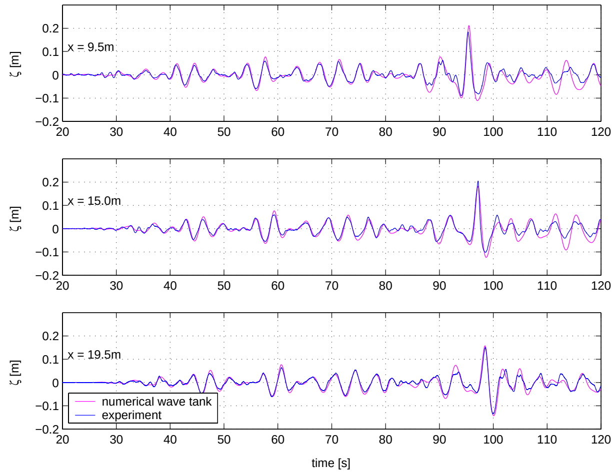

Fig. 10: Irregular sea (JONSWAP spectrum, $T_P = 4.2$ s, $H_s = 0.1$ m) with integrated wave packet ($H_{max} = 0.35$ m) at different positions in the wave tank. Numerical simulation based on RANSE/ VOF. Generation of the wave maker control signal for both model tank and numerical wave tank data using the modified theory.

and measurement of a wave packet with a JONSWAP spectrum at different positions in the wave tank (tank dimensions: length 80 m, width 4 m, water depth 1.5 m, piston type wave generator). It can easily be seen, that the phases and amplitudes are well predicted by the numerical wave tank. Wave packets can e.g. be used to simulate extreme waves (Kühnlein et al. (2002)) or to model high wave groups within a natural sea state like in Fig. 10: It shows the simulation of the wave packet from Fig. 9 integrated to irregular seas.

As a RANSE solver is used for this wave tank the duration of the calculation is significantly higher as compared to the numerical wave tank based on potential theory and FEM. To make use of the benefits of both methods a combined approach is recommended: potential theory as long as no wave breaking occurs, and RANSE code if breaking is encountered.

Both numerical wave tanks are not capable to transform a given wave train backwards to the position of the wave generator. In order to generate a predetermined wave sequence at a target location the numerical wave tank has to be combined with the modified approach or optimization routines (Clauss and Steinhagen (2000)).

Experimental investigation of offshore structures

For the experimental investigation of wave-structure interaction of stationary offshore structures it is important to know the exact wave train at the model position. Measurements close to the model are disturbed by radiation and diffraction. Using the presented modified non-linear approach the wave train can be calculated at any position of the model tank.

Fig. 11 (top) presents the wave train of the so called New Year Wave recorded in the North Sea and simulated in the wave tank using the above introduced modified approach. This rogue wave with an unusual H_{max}/H_s ratio of 2.15 is applied to both the experimental and numerical investigation of rogue wave impact on the structural (splitting) forces of a semisubmersible (Fig. 11, Clauss et al. (2003b)). Wave sequences calculated by the modified non-linear approach have also been successfully applied to the investigation of rogue wave impacts on the vertical bending moments of a stationary crane vessel (Clauss et al. (2003a)) and an FPSO ship (Clauss et al. (2004b)).

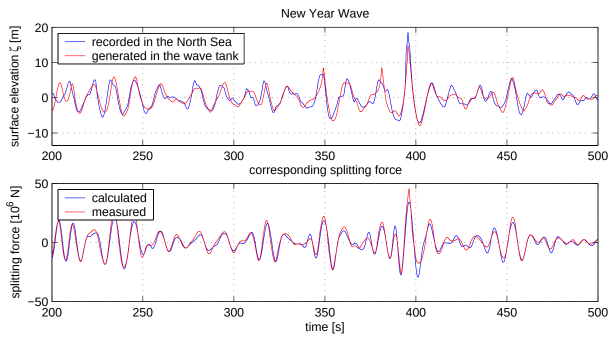

Fig. 11: Top: comparison of recorded New Year Wave and wave tank simulation (scale 1:81). Bottom: measured and calculated splitting forces of the semisubmersible due to the rogue wave impact (all data presented as full scale data).

Experimental investigation of intact stability

For the experimental investigation of intact stability with regard to both extreme and resonance phenomena the wave train as the beginning of the cause reaction chain can be directly compared to the reaction of the cruising ship since all time series are calculated resp. measured in the moving reference frame of the ship model.

For controlled capsizing tests (Clauss and Hennig (2003)) we generate a regular wave with an embedded "Three Sisters wave" sequence at a moving reference frame. Fig. 12 shows a wave packet within a regular wave measured at a stationary wave probe close to the wave board ($x = 297.8$ m, model scale 1:34). It is transformed to the position of the cruising ship. As shown in Fig. 12 this resulting wave sequence is quite regular and contains the target "Three Sisters wave" at the location of interaction with the cruising ship. Thus, high roll angles (lower diagram) can be induced by generating tailored moving reference frame wave trains deterministically.

Numerical predictions can also be directly compared to model tests applying the following scheme: The wave train used in the numerical simulation for assessing ship safety is given as full scale target wave train (Fig. 13 top) and transformed to model scale (1:34). Now the modified non-linear approach is applied to obtain the wave train at the position of the wave maker. Thus the corresponding control signal for driving the wave maker (signals for upper and main flap of double flap wave maker at Hamburg Ship Model Basin). The generated wave train is registered at a stationary wave probe close to the wave maker and transformed to $x = 125$ m (compare target wave train). The ship position is measured during the test. Thus, the stationary wave train is transformed to the moving reference frame of the ship model to obtain the wave as experienced by the ship. The resulting (measured) roll motion can be directly compared to this wave train (Fig. 13 bottom). The same test data is used for a visual comparison of numerical simulation and model test results in Cramer et al. (2004).

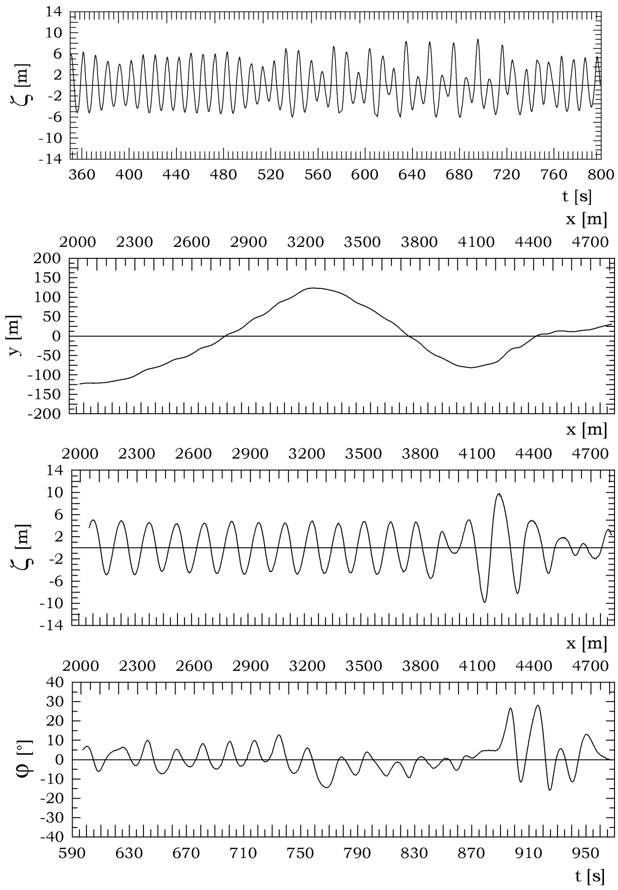

Fig. 12: Roll motion of a multipurpose vessel ($GM = 0.44$ m, $v = 14.8$ kn und $\mu = \pm 20°$) in a regular wave from astern ($\lambda = 159.5$ m, $\zeta_{\text{crest}} = 5.8$ m) with proceeding high transient wave packet (compare Fig. 7).

Discussion, conclusions and perspective

In this paper a modified non-linear approach for modelling wave propagation is presented which provides

- transformation of arbitrary wave trains from stationary positions to other arbitrary positions, especially
- upstream transformation to the wave board to get the corresponding wave maker signal, and

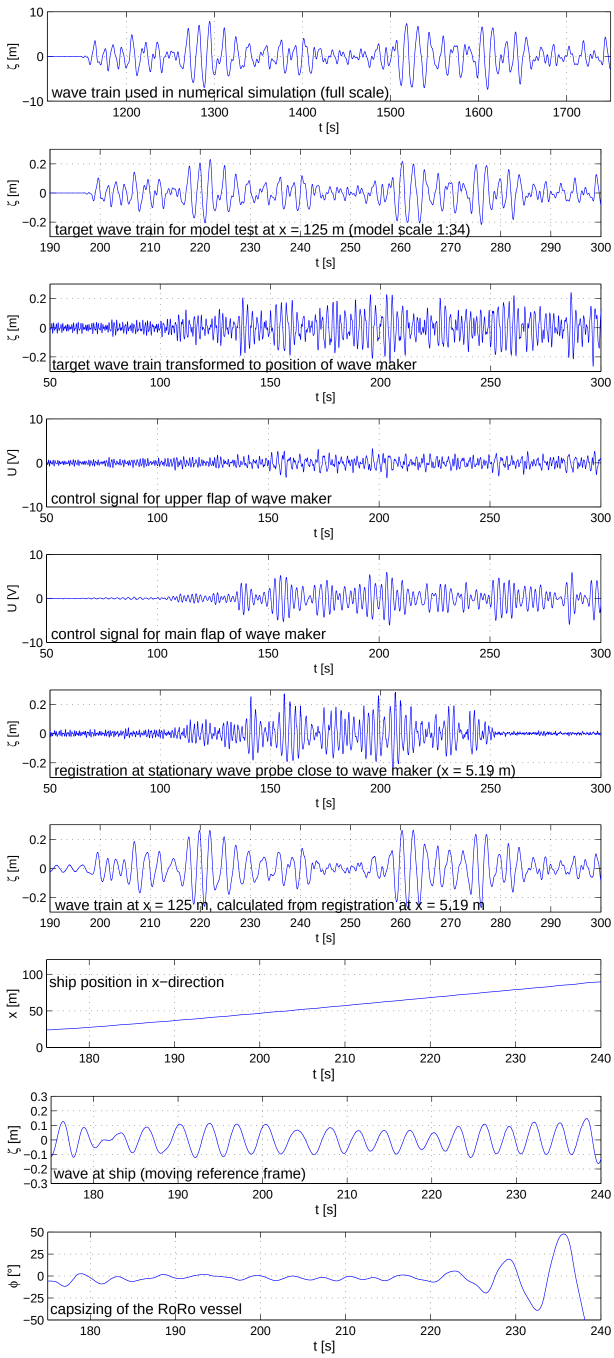

Fig. 13: Experimental realization of dangerous wave sequences from numerical capsize simulations: Starting with the target wave train the wave at the position of the wave maker is calculated using the modified non-linear approach to get the corresponding control signals. From registration at a stationary wave probe close to the wave maker the stationary wave train at $x = 125$ m is given by the modified theory (compare target wave) and transformed to the position of the ship model (scale 1:34) to obtain the moving reference frame wave train which can be compared to the roll motion of the RoRo ship which subsequently capsizes. See also Fig. 3 in Cramer et al. (2004).

- generation of a all kinds of deterministic wave trains,
- transformation of arbitrary wave trains from stationary positions to a moving reference frame of a cruising structure.

The modified non-linear approach is fast and precise and applicable in day-to-day use for experimental investigations. The method can be adapted easily for new requirements as the implementation of different wave theories is possible.

Compared to the numerical wave tanks the method is capable of backward transformation of wave trains and is therefore ideally suited for generating wave board control signals. As target signal, measurements from full scale or arbitrary synthesized wave trains, e.g. from optimization processes can be used. The potential of the procedure is demonstrated by simulating different wave scenarios like wave packets, irregular and regular seas with embedded wave packets.

Furthermore, the method allows the transformation of given wave sequences into the moving reference frame of a cruising vessel. With this technique wave scenarios can be analyzed from the point of view of a sailing ship.

A wide range of applications of the presented non-linear wave calculation procedure is given:

- Validation of a numerical wave tank based on potential theory in combination with a Finite Element Method
- Validation of a numerical wave tank using a RANSE code and a dynamic mesh approach
- Experimental investigation of seakeeping characteristics of offshore structures
- Experimental investigation of intact stability and comparison with numerical simulations

Both numerical wave tanks provide detailed knowledge of the pressure, velocity and acceleration fields in the entire fluid domain. This information can be used in a next step to investigate wave/structure interaction.

Recapitulating, the modified non-linear theory is a powerful tool to face the complex tasks related to the experimental investigation of extreme structure behaviour such as large rolling, capsizing, and rogue wave impacts.

In conclusion, the modified non-linear theory is an excellent tool to generate deterministic wave trains at arbitrary positions (even in a moving reference frame) as this is the only procedure which can calculate upstream to determine wave board motions and the associated control signals. In calculating the wave elevation downstream, the above method agrees well with the numerical wave tanks based on potential theory/ FEM and RANSE/ VOF (Fluent). Thus, the additional capabilities of numerical wave tanks, i. e. the determination of wave field characteristics (velocity, acceleration and pressure fields) and of the RANSE/ VOF method (consideration of wave breaking) can be ideally combined with the above method.

As a consequence, the combination of the proposed procedures is an innovative tool kit to analyze the interaction of wave and structure, and to investigate the structure behaviour in all kinds of wave scenarios.

Acknowledgment

The authors are indebted to the German Federal Ministry of Education, Research, and Technology, BMBF, for funding the project SinSee (FKZ 03SX145). The authors also want to express their gratitude to the German Research Foundation (DFG) for funding the research project "Extreme Seegangsereignisse" and to the European Union for financing the research project MAXWAVE (contract number EVK-CT-2000-00026). Many thanks go to Mr. Michael Alex for preparing so many figures.

References

G.F. Clauss and J. Hennig. Deterministic Analysis of Extreme Roll Motions and Subsequent Evaluation of Capsizing Risk. In *STAB 2003 - 8$^{\text{th}}$ International Conference on the Stability of Ships and Ocean Vehicles*, Madrid, Spain, 2003.

G.F. Clauss, J. Hennig, C.E. Schmittner, and W.L. Kühnlein. Non-linear Calculation of Tailored Wave Trains for the Experimental Investigation of Extreme Structure Behaviour. In *OMAE 2004 - 23rd International Conference on Offshore Mechanics and Arctic Engineering*, Vancouver, Canada, 2004a. OMAE2004-51195.

G.F. Clauss, C.E. Schmittner, and J. Hennig. Simulation of Rogue Waves and their Impact on Marine Structures. In *MAXWAVE Final Meeting, 8-10, October*, Geneva, Switzerland, 2003a.

G.F. Clauss, C.E. Schmittner, J. Hennig, C. Guedes Soares, N. Fonseca, and R. Pascoal. Bending Moments of an FPSO in Rogue Waves. In *OMAE 2004 - 23rd International Conference on Offshore Mechanics and Arctic Engineering*, Vancouver, Canada, 2004b. OMAE2004-51504.

G.F. Clauss, C.E. Schmittner, and K. Stutz. Freak Wave Impact on Semisubmersibles - Time-domain Analysis of Motions and Forces. In *ISOPE 2003 - 13th International Offshore and Polar Engineering Conference*, Honolulu, USA, 2003b. ISOPE 2003-JSC-371.

G.F. Clauss and U. Steinhagen. Numerical simulation of nonlinear transient waves and its validation by laboratory data. In *Proceedings of 9th International Offshore and Polar Engineering Conference (ISOPE)*, volume III, pages 368–375, Brest, France, 1999.

G.F. Clauss and U. Steinhagen. Optimization of transient design waves in random sea. In *Proceedings of 10th International Offshore and Polar Engineering Conference (ISOPE)*, volume III, pages 229–236, Seattle, USA, 2000.

H. Cramer, K. Reichert, K. Hessner, J. Hennig, and G. F. Clauss. Seakeeping Simulations and Seaway Models and Parameters Supporting Ship Design and Operation. In *PRADS 2004 - 9th International Symposium on Practical Design of Ships and Other Floating Structures*, Lübeck-Travemünde, Germany, 2004.

Fluent. *FLUENT 6.1 Users Guide*. Fluent Inc., New Hampshire, USA, 2003.

S. Haver. Some Evidences of the Existence of Socalled Freak Waves. In *Rogue Waves 2000*, Brest, France, 2000.

B. Kinsman. *Wind Waves*. Prentice Hall Inc., Englewood Cliffs, New York, 1965.

W.L. Kühnlein, G.F. Clauss, and J. Hennig. Tailor Made Freak Waves Within Irregular Seas. In *OMAE 2002 - 21st Conference on Offshore Mechanics and Arctic Engineering*, Oslo, 2002. OMAE2002-28524.

L. Skjelbreia. Gravity waves — stokes' third order approximation. *California Research Corporation*, 1959.

U. Steinhagen. Synthesizing nonlinear transient gravity waves in random seas. *Dissertation*, Technische Universität Berlin (D 83), 2001.

J. Wolfram, B. Linfoot, and P. Stansell. Long- and short-term extreme wave statistics in the North Sea: 1994-1998. In *Proceedings of Rogue Waves 2000*, pages 363–372, Brest, FRANCE, 2000.