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A PHASE-AMPLITUDE ITERATION SCHEME FOR THE OPTIMIZATION OF DETERMINISTIC WAVE SEQUENCES

Christian Schmittner *
Manoeuvring and Seakeeping Department
MARIN
Netherlands
c.schmittner@marin.nl

Sascha Kosleck
Ocean Engineering Section
Technical University Berlin
Germany
kosleck@naoe.tu-berlin.de

Janou Hennig
Offshore Department
MARIN
Netherlands
j.hennig@marin.nl

ABSTRACT

For the deterministic investigation of extreme events like capsizing, broaching or wave impacts, methods for the generation of deterministic wave sequences are required. These wave sequences can be derived from full scale measurements, numerical simulations or other sources. Most methods for the generation of deterministic wave sequences rely as a backbone on linear wave theory for the backwards transformation of the wave train from the target position in the wave basin to the position of the wave maker. This implies that nonlinear wave effects are not covered to full extend or they are completely neglected. This paper presents a method to improve the quality of the generated wave train via an experimental optimization. Based on a first wave sequence generated with linear wave theory and measured in the wave basin, the phases and amplitudes of the wave maker control signal are modified in frequency domain. The iteration scheme corrects both, shifts in time and in location, resulting in an improved deterministic wave train at the target location. The paper includes results of this method from three different basins with different types of wave generators, water depth and model scales. In addition, this method is applied to a numerical wave tank where the waves can be optimized before the actual basin testing.

INTRODUCTION

Ocean waves vary in shape and size determined by height, length, propagation velocity and direction. These irregularities of ocean waves can be described with a random wave model, where the sea state is supposed to consist of a superposition of component waves, each with its own amplitude, frequency and direction of propagation and velocity. For the investigation of extreme phenomena like e.g. capsizing, broaching or impacts of extreme waves, methods for the deterministic generation of wave sequences in the wave basin are required, as with statistical methods the effect of extreme single wave events may not be covered.

For these types of model tests, techniques for the generation of wave scenarios with predefined wave pattern and predefined local wave characteristics are required. Therefore, the scope of this paper is to provide a method for the generation of a deterministic wave sequence to answer such questions by model tests in the wave tank.

PHASE-AMPLITUDE ITERATION SCHEME

Since conventional numerical methods are still not accurate, or if accurate, not fast enough to generate special wave environments, as alternative a *phase-amplitude iteration scheme* for synthesizing deterministic wave sequences is presented. The advantage of this *phase-amplitude iteration scheme* is the inherent inclusion of all nonlinear wave effects by using a physical wave tank. This scheme modifies the phase angles and amplitudes of the control signal in frequency domain dependent on the differences between target and measured wave train.

The basic idea behind this generation scheme is based on a method proposed by Chaplin [1] who improved the accuracy of a focused wave train. Starting with a given target wave train

*Address all correspondence to this author.

(a wave packet at the focussing point) and the corresponding control signal for the wave generator, the wave train is recorded in the wave basin. From the comparison of the recorded phase angles ($\varphi_{recorded}$) at target location with the target phase angles (φ_{target}) in frequency-domain, the new phase angles of the control signal are calculated:

$$\varphi_{new} = \varphi_{old} - 2 \cdot (\varphi_{target} - \varphi_{recorded}) \tag{1}$$

with:

φ_{old}	Phase angles of the initial or previous control signal
φ_{new}	New control signal phase angles
$\varphi_{recorded}$	Phase angles of the registration at target location
φ_{target}	Phase angles of the target wave train at target location

The phase shift applied is the opposite phase shift determined by comparison of target phase angles and recorded phase angles. Thus, convergence can only be achieved if the resulting phase shift is less than this. This iteration scheme was successfully applied by Chaplin to the generation of wave packets (in-phase superposition of component waves).

In this paper, the iteration scheme is extended, in order to generate more complex irregular wave sequences. The target wave sequences can either be records from full scale measurements or e.g. synthesized from parameters applying the optimization approach presented in [2]. The target phases are calculated from the target signal by Fourier transform and phases of the control signal are modified according to Eq. 1.

The original scheme modifies only the phases, knowing that at the focusing point of a wave packet all component waves are superimposed in phase, whereas for irregular wave trains the phases are more or less randomly distributed. In addition to the original scheme, the method is extended to deal with arbitrary wave sequences at target location and to modify also the amplitudes of the component waves. To apply the iteration scheme also to irregular sea states the target phases φ_{target} are derived from a target wave train. The amplitudes of the component waves are scaled within the iteration scheme with the ratio of target amplitude to the recorded amplitude [3]:

$$a_{new} = a_{old} \cdot s \cdot \left(\frac{a_{target}}{a_{recorded}} \right) \tag{2}$$

with:

a_{old}	Amplitudes of component waves of the initial or previous control signal
a_{new}	Amplitudes of component waves of new control signal
a_{target}	Amplitudes of the registration at target location
$a_{recorded}$	Amplitudes of the target wave train at target location
s	Scaling factor

In consequence, the spectrum of the wave train to be generated is iteratively improved to fit the spectrum of the target wave train. The scaling factor s is introduced in order to speed up the iteration process. If the control signal gives a registration with a spectrum close to the desired spectrum s is set to 1. Only for significant deviations between the spectra of the target and initial registration larger values can be used to speed up the optimization process (reduce the number of iteration steps).

In the following section this *phase-amplitude iteration scheme* is applied to three different wave basins. As performing iteration steps in the wave basin is a time consuming and therefore costly process, the method is in addition applied to a numerical wave tank where a wave sequence can be optimized before actually doing tests in the basin.

PRACTICAL APPLICATION TO PHYSICAL WAVE TANK

In order to assess the feasibility of this method for the practical generation of deterministic extreme wave sequences in the wave tank the so-called *New Year Wave* is selected as an extreme wave sequence and will be created in different wave basins. The *New Year Wave* is a giant wave ($H_{max} = 25.63$ m) with a crest height of $\zeta_c = 18.5$ m that hit the *Draupner* jacket platform on January 1^{st}, 1995 [4]. During this time the significant wave height was $H_s = 11.92$ m resulting in a ratio of $H_{max}/H_s = 2.15$ showing that this wave is of remarkable height.

The goal is to generate this wave applying the *phase-amplitude iteration scheme* in the following wave basins:

- Shallow Water Basin at MARIN, Netherlands
  - Length: 220 m
  - Width: 15.8 m
  - Water depth: 1.0 m
  - Target location: 50 m
  - Scale: 1:70
  - Piston type wave generator
- Wave Tank TUB, Germany
  - Length: 80 m
  - Width: 4 m
  - Water depth: 1.5 m
  - Target location: 30 m

- Scale: 1:81
- Piston type wave generator

- Small Wave Tank TUB, Germany
  - Length: 12 m
  - Width: 0.3 m
  - Water depth: 0.4 m
  - Target location: 6 m
  - Scale: 1:175 and 1:250
  - Flap type wave generator

As the dimensions of the basins vary significantly, different scales are applied for the wave generation. At MARIN's Shallow Water Basin the wave is generated at scale 1:70, in the Wave Tank at TUB a scale of 1:81 is selected and for the Small Wave Tank at TUB scales of 1:175 and 1:250 are applied.

As a first step for the generation of the *New Year Wave*, from the down scaled target wave train, a first control signal is calculated by linear wave theory, i.e. the target wave train is transformed backwards from the target location to the location of the wave generator. This wave at the wave maker is than multiplied by the wave makers hydrodynamic and electric transfer function giving the starting control signal for the *phase-amplitude iteration scheme*. The wave is then generated and measured in the wave tank. Afterwards the *phase-amplitude iteration scheme* is applied yielding a second, improved control signal. Depending on the quality of the realized wave the iteration scheme can be applied several times more in order to achieve better agreement between target wave and measured wave at target location. Fig. 1 gives an idea of the procedure of the method applied. Up to now the quality of the generated wave train is evaluated visually by comparison with the target wave train. For a more impartial judgement of the wave quality a measure of merit can be introduced in the future.

SHALLOW WATER BASIN AT MARIN

The first example presented shows the synthesization of the *New Year Wave* in the Shallow Water Basin of MARIN. Fig. 2 (top diagram) presents the wave generated with the initial control signal based on linear wave theory. The target location is 50 m downstream from the wave board and the target time is 250 s (full scale). The comparison of the generated wave to the target wave train shows obvious differences which may be caused by wave-wave interaction or nonlinear amplitude dispersion. However, as the method is improving the control signal based on the difference between measured and target wave, the reasons for this discrepancies are not essential to know in detail.

After applying the *phase-amplitude iteration scheme* once, the bottom diagram of Fig. 2 gives the improved wave train. The phasing of the wave train is clearly better. In particular around the focusing point of the extreme wave the phasing has improved significantly. Thus, the method is able to enhance the quality of

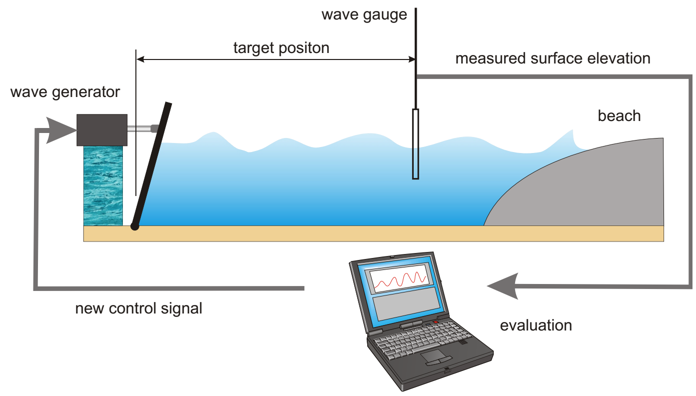

Figure 1. OPTIMIZATION OF MODEL WAVES. THE WAVE SEQUENCE IS GENERATED, MEASURED, EVALUATED AND MODIFIED IN ORDER TO IMPROVE THE WAVE QUALITY WITH RESPECT TO THE TARGET WAVE TRAIN.

the generated wave train. Due to the relative high quality of the first control signal, i.e. the amplitudes of the component waves are as required and the phasing is not too far of, within one iteration step a significant improvement can be observed. Nevertheless, the iteration scheme is not able to correct the extreme wave height of the embedded rogue wave to full extend. Further application of the iteration scheme does not improve the wave train any more. For further improvements of local wave characteristics optimization methods as described in [5] could be applied. However, for many applications the achieved accuracy might be sufficient as the result was obtained fast and is therefore applicable in the wave basin.

LARGE WAVE TANK AT TUB

As a second example for the practical application of the method the *New Year Wave* is generated in the wave tank at TUB. Model scale 1:81 is selected in order to match with the model scale selected for the investigation of offshore structures in Rogue Waves [6]. In consequence, the water depth is not scaled accordingly. Fig. 3 presents the improved wave train after applying the iteration scheme twice, i.e. the wave has been generated in total three times in the basin.

SMALL WAVE TANK AT TUB

The third example of wave synthesization by the iteration scheme is done in the Small Wave Tank at TUB at a water depth of 0.4 m. For the wave generation, model scales 1:175 and 1:250 are selected which correspond to 70 m and 100 m water depth at full scale. For the optimization no control signal as in the previous cases has been calculated beforehand but an existing control signal for a wave packet (focussed wave) is used as a starting point. This initial control signal is far off a control signal

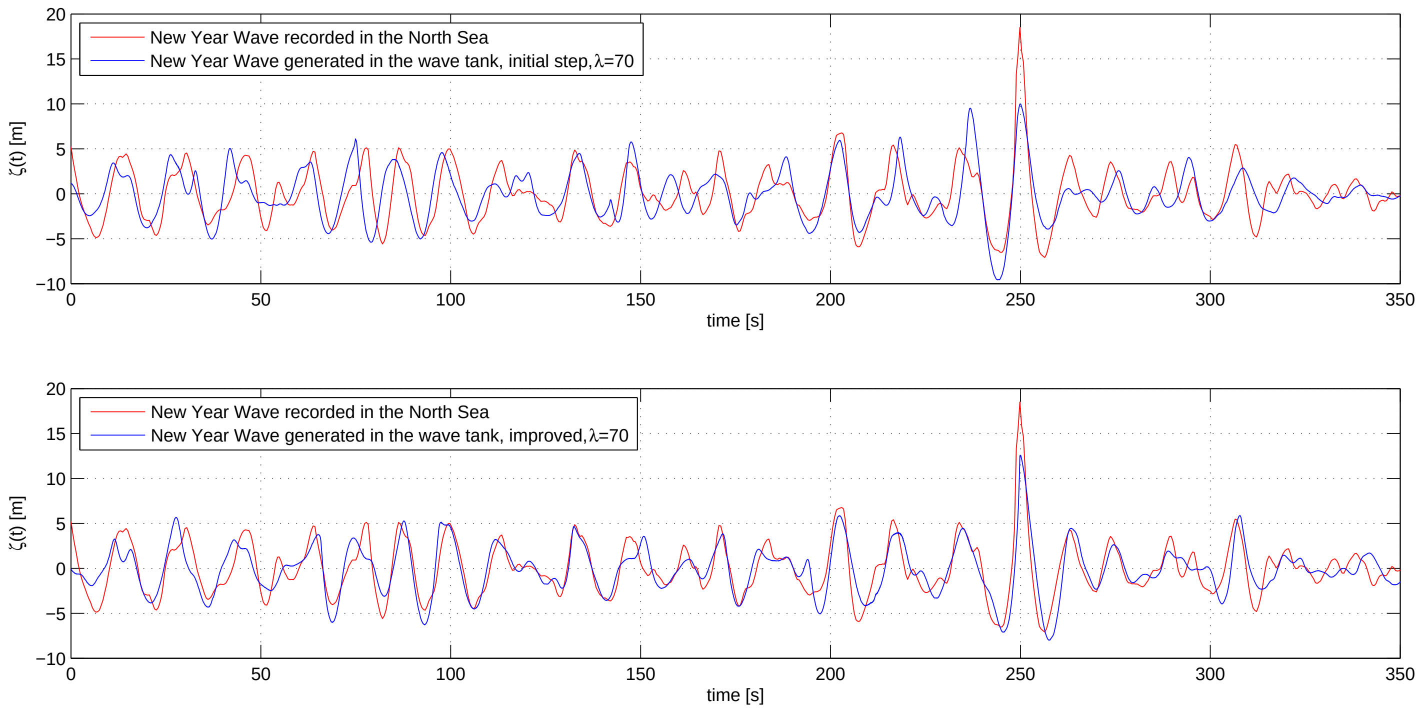

Figure 2. OPTIMIZED WAVE TRAIN AT TARGET POSITION ($x = 50$ m, WATER DEPTH $d = 1.0$ m, 70 m FULL SCALE) AFTER ONE ITERATION STEP OF THE PHASE-AMPLITUDE ITERATION SCHEME IN COMPARISON WITH THE RECORDED NEW YEAR WAVE SEQUENCE (WAVE TANK SIMULATION AT SCALE 1:70, PRESENTED AS FULL SCALE DATA).

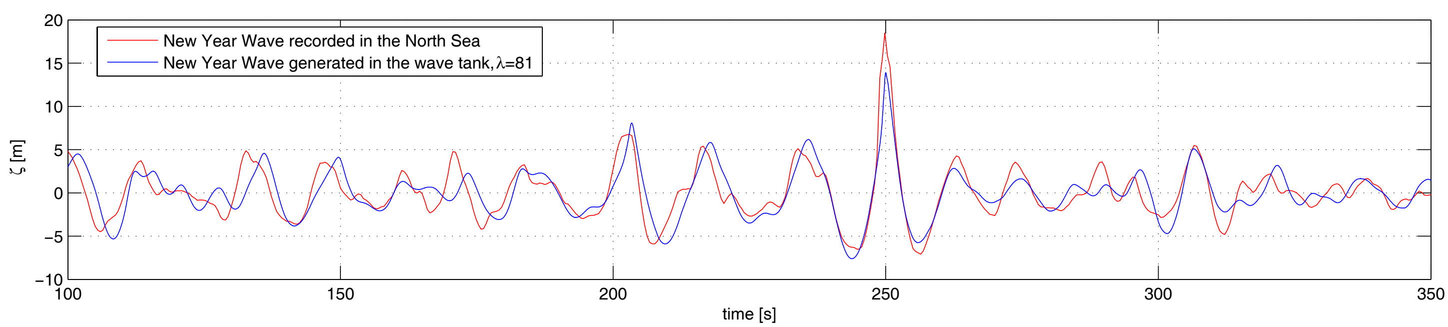

Figure 3. OPTIMIZED WAVE TRAIN AT TARGET POSITION ($x = 30$ m, WATER DEPTH $d = 1.5$ m, 121.5 m FULL SCALE) AFTER TWO ITERATION STEPS OF THE PHASE-AMPLITUDE ITERATION SCHEME IN COMPARISON TO RECORDED NEW YEAR WAVE SEQUENCE (WAVE TANK SIMULATION AT SCALE 1:81, PRESENTED AS FULL SCALE DATA).

for generating the desired wave sequence and has been selected in order to show that the *phase-amplitude iteration scheme* is not depending on a good starting point or detailed knowledge on wave makers transfer functions.

However, after ten (scale 1:175), 23 iteration steps (scale 1:250), respectively, a good agreement with the target wave sequence is observed. The high number of iterations could be reduced by selection of a larger scaling factor s for modifying the spectral shape in less iterations. Fig. 4 and Fig. 5 present the results of the iteration process in the Small Wave Tank.

As already mentioned, the waves in the Small Wave Tank are generated starting with a control signal for a wave packet. Thus, the phases and amplitudes of the component waves are definitely not similar to the target phases and amplitudes and have therefore to be modified by the iteration scheme. Fig. 6 shows the evolution of the wave train at target location within ten iteration steps for the optimization at scale 1:250. The time trace on top is generated by the control signal for a focused wave with concen-

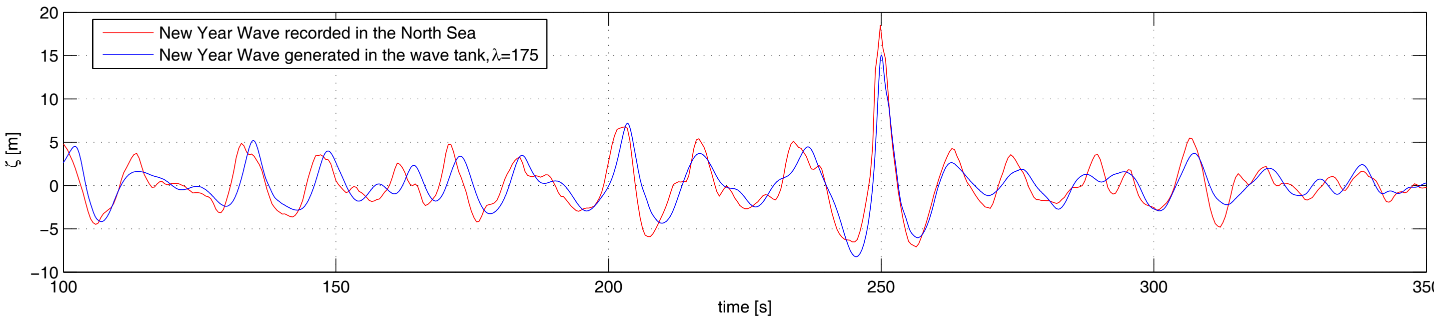

Figure 4. OPTIMIZED WAVE TRAIN AT TARGET POSITION ($x = 6$ m, WATER DEPTH $d = 0.4$ m, 70 m FULL SCALE) AFTER 23 ITERATION STEPS IN COMPARISON WITH THE RECORDED NEW YEAR WAVE SEQUENCE (WAVE TANK SIMULATION AT SCALE 1:175, PRESENTED AS FULL SCALE DATA).

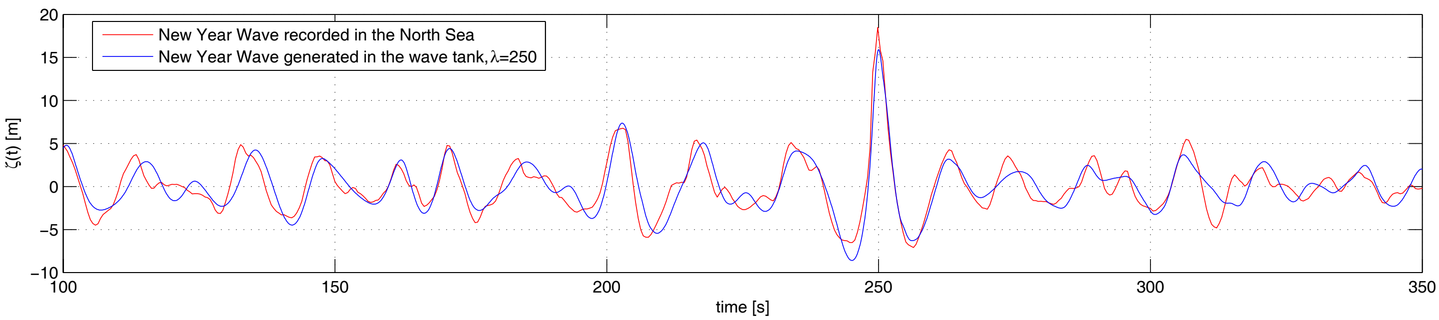

Figure 5. OPTIMIZED WAVE TRAIN AT TARGET POSITION ($x = 6$ m, WATER DEPTH $d = 0.4$ m, 100 m FULL SCALE) AFTER TEN ITERATION STEPS IN COMPARISON WITH THE RECORDED NEW YEAR WAVE SEQUENCE (WAVE TANK SIMULATION AT SCALE 1:250, PRESENTED AS FULL SCALE DATA).

tration point further down stream. After the first iteration (second time trace from top) already the general pattern of the irregular wave train emerges, i.e. the phases are improved significantly within one iteration step. The wave train improves continuously during the following iteration steps.

Further application of the iteration scheme, beyond the ten iterations presented, is not improving the accuracy of the wave train any further. With additional iterations the quality of the waves will stay about the same as the last iteration step shown, with only small variations in quality. As a consequence, if a wave train is not further improving with the following iteration step, the iteration scheme can be stopped. As already mentioned the assessment of the quality has been done visually. A further improvement to the scheme would be a measure of merit that takes into account the overall compliance of the generated wave train with the target wave train as well as the local wave characteristics of the embedded rogue wave.

It is interesting to note, that the timing of the highest wave is already correctly reproduced after the first iteration step. This indicates that phase shifts are relatively easily achieved. The adjustment of the amplitudes of the component waves takes quite some iteration steps more. As a consequence, in particular the spectrum of the initial control signal should be as good as possible in order to limit the number of iteration steps required.

SUMMARY OF WAVE TANK RESULTS

The simulations at all four model scales presented above show that the *phase-amplitude iteration scheme* is able to realize complex wave sequences for different wave tanks and model scales within a reasonable accuracy. The number of iterations required to obtain good results depends on the quality of the initial control signal. For the scales of 1:70 and 1:81, a control signal is calculated based on linear theory and after only one or two iteration steps, respectively, the wave train is in good agreement with the target wave train. The iteration scheme is also able to deal with "wrong" control signals with the consequence that more iteration steps are required. But even with a bad initial control signal (see Fig. 6) the *phase-amplitude iteration scheme* is capable of synthesizing the target wave train. The quality of the waves that can be achieved is independent on the quality of the first control signal, only the number of iteration steps needed varies.

In general, the iteration scheme can also be applied without

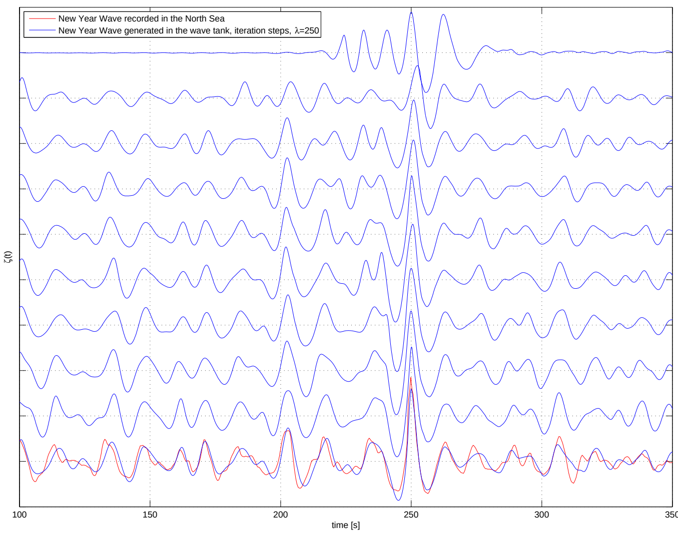

Figure 6. OPTIMIZATION OF WAVE TRAIN BY SEVERAL ITERATION STEPS STARTING FROM A CONTROL SIGNAL FOR A WAVE PACKET. (WAVE TANK SIMULATION AT SCALE 1:250, PRESENTED AS FULL SCALE DATA).

knowing the transfer functions of the wave generator, because for this method the wave generation process is treated like a black box. Only the input (control signal) and output (measured time trace) are considered.

However, for the application of this method, it is of crucial importance that the start of the wave generator and the begin of the measurement are synchronized and the process is repeatable. Small differences in synchronization will cause problems with convergence.

The differences in the maximum wave heights of the experimentally simulated and the recorded *New Year Wave* can be partly attributed to the limited bandwidth of the wave generators and to the fact that the *New Year Wave* is close to breaking due to high frequency contents. Thus, the generated wave height is always lower than requested, although the iteration scheme was extended to modify both, the phases and amplitudes of the component waves.

Interesting to note: The smaller the model scale, the higher the single extreme wave. The best fit is observed for the wave generated at model scale 1:250. Normally, one would expect that at this model scale it is more difficult to generate the higher frequencies due to limitations of the wave maker and in consequence the wave height of the extreme wave is smaller. This effect seem to be counteracted in the selected test case by the fact that at a smaller model scale the simulated water depth is larger and thus shallow water effects play probably a minor role. In consequence, the generated wave is longer stable and not breaking giving a larger extreme wave height. Comparing the results at scale 1:175 and 1:70, which are both realized for 70 m full scale water depth, one would expect similar results. Nevertheless, at the smaller scale the match between target wave train and realized wave train is better. This result is surprising but might be due to the fact that at scale 1:175 the target location was selected closer to the wave board ($x = 6$ m, 1050 m at full scale) than at scale 1:70 ($x = 50$ m, 3500 m at full scale). As the wave train is breaking several times before reaching the target location, more energy might relatively be lost at scale 1:70 due to the longer propagation distance.

A principle limitation of the iteration scheme is that modifications to the amplitudes and phases of the component waves are influencing the entire time series as the method is based on Fourier transformation. In consequence, the entire time trace is modified by the scheme without the possibility to improve a single dedicated wave. Therefore, also the maximum length of a wave train that can be generated with good quality will be limited.

Summarizing, this iteration process can be used for the fast and precise generation of wave trains. Due to the limited number of iterations needed this method can also be applied to large wave tanks. If a better accuracy is required for local wave characteristics the wave train could further be improved by an experimental optimization processes as e.g. described in [7].

APPLICATION TO A NUMERICAL WAVE TANK

As iteration steps in the tank are still time consuming and therefore expensive, the idea is to optimize a deterministic wave train first by numerical simulations, i.e. within a numerical wave tank. The precondition for this is, that the numerical wave tank is able to calculate wave propagation accurately based on the wave maker's control signal. Furthermore, to be practically applicable the calculations have to be performed within a reasonable time frame, e.g. within a few hours.

The numerical wave tank WAVETUB applied in this paper was developed by Steinhagen [8] at the Technical University Berlin. The two dimensional nonlinear free surface flow problem is solved in time domain using potential theory: The fluid is inviscid and incompressible, and the flow is irrotational. Long-crested nonbreaking waves are considered. For the discretization of the fluid domain, the Finite Element Method is applied as proposed by [9]. 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 using the finite element method. From this solution, the velocities at the free surface are determined by second-order differences.

To develop the solution in time, 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

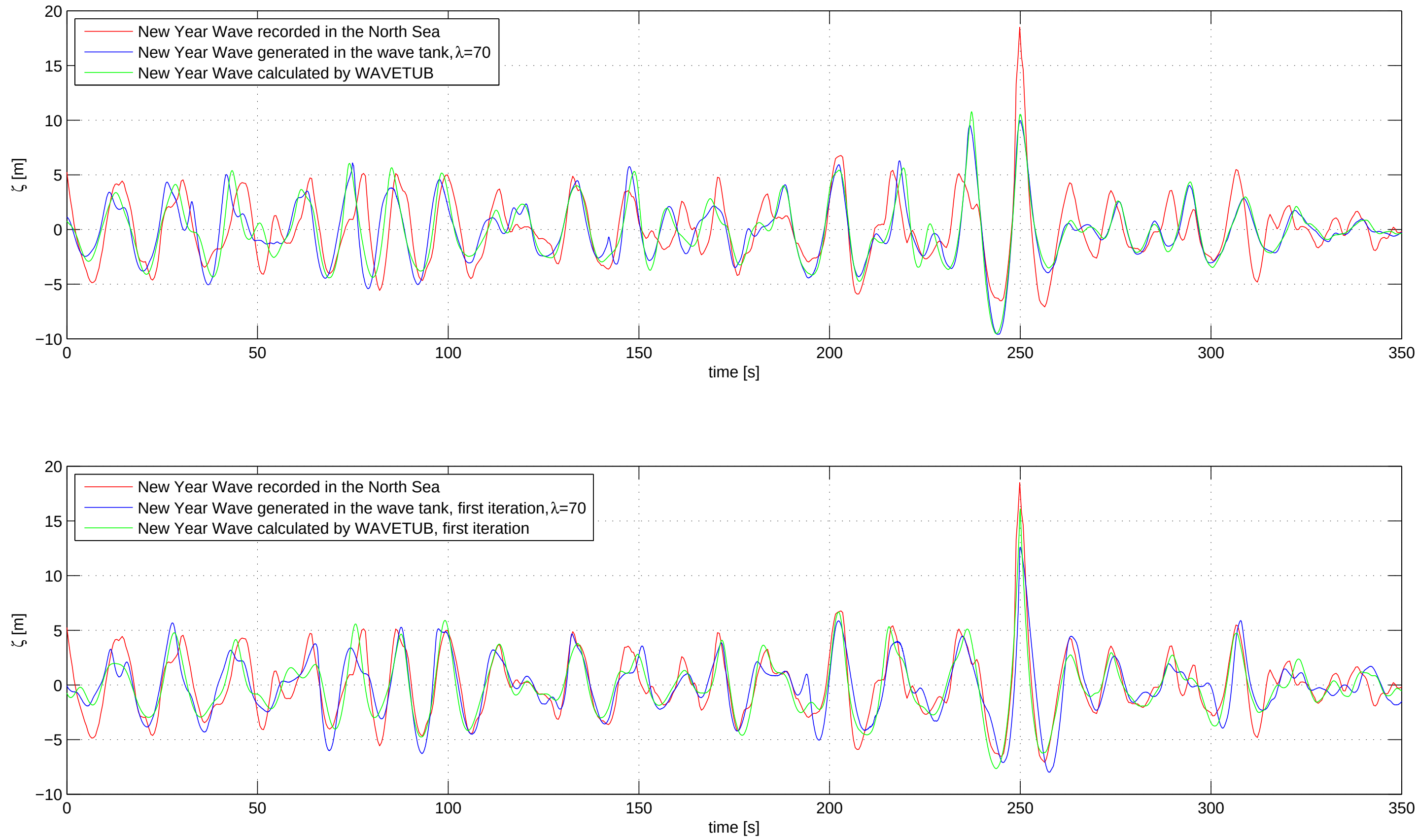

Figure 7. TOP: NUMERICAL SIMULATION AND WAVE TANK REALIZATION RESULTING FROM THE SAME INITIAL CONTROL SIGNAL; BOTTOM: NUMERICAL SIMULATION AND WAVE TANK REALIZATION BASED ON (DIFFERENT) IMPROVED CONTROL SIGNALS APPLYING THE PHASE-AMPLITUDE ITERATION SCHEME.

time step is reached. The numerical wave tank is able to simulate wave generators of types piston, single flap and double flap (and combinations of these). A complete description of this numerical wave tank can be found in [8] and [10].

For the application of the iteration scheme, as a first step, the control signal which was calculated based on linear wave theory is used for simulating the wave propagation by WAVETUB. The same first control signal as used for the generation of the waves in MARIN's Shallow Water Basin is used. In consequence, the simulated wave and the measured wave should give the same time trace at target location for the initial step. Target location was 50 m from the wave board. Fig. 7 (top diagram) presents the comparison of the target wave train as measured in the North Sea and the numerically simulated wave as well as the generated wave in the wave basin. Note, both the simulated and generated wave are based on the same wave maker control signal. The simulation and wave basin measurements are quite in line, i.e. the phasing is consistent and differences can be found in details.

In analogy with the experimental approach, based on the result of the numerical simulation a new control signal is now calculated for the next iteration step. The wave is then simulated again with WAVETUB resulting in the simulated time trace as presented in Fig. 7 (bottom diagram). Note, the numerical simulation and the experimental result are based on different control signals. The control signal for the experiment is derived from the registration in the wave tank and the control signal for the calculation is derived from the numerical simulation. A comparison of simulated wave and measured wave shows that the *phase-amplitude iteration scheme* applied to the numerical simulation modifies the control signal and thus the wave at target location in a similar way as observed in the experiments. In consequence, this approach can be used to improve wave trains numerically before the actual testing in the basin.

CONCLUSIONS

This paper presents a smart iteration scheme to improve the quality of a deterministic wave train in comparison to wave trains generated based on linear theory. The iteration scheme modifies the amplitudes and phases of the component waves of the control signal in frequency domain. In consequence, the location and timing of the entire wave train can be modified and adapted to the target parameters. The number of iterations required to obtain a final solution is depending on the quality of the starting control signal. However, the quality of the generated wave train is not depending on the quality of the starting control signal. The method is able to improve the overall accuracy of a wave train. Optimization of local details is limited and more advanced methods are required. The method is applicable with a minimum knowledge of the wave generator and the wave generation process as this is treated like a black box, i.e. for modification of the control signal (input) only the output (measured wave) is considered.

The combination with a numerical wave tank enables the iteration scheme to be applied beforehand in numerical simulations in order to save basin time. However, this valuable approach requests for a precise and reliable method to calculate wave propagation for the selected wave tank. As the *phase-amplitude iteration scheme* is fast, accurate and easy to apply it will be considered for future use at MARIN.

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