Modelling of Extreme Waves Related to Stability Research

Janou Hennig[1] and Frans van Walree[1]

1. *Maritime Research Institute Netherlands,(MARIN), Wageningen, the Netherlands*

Abstract: The paper deals with several aspects of extreme wave modeling in model basins. The effects of directional spreading, steepness and distance from the wave maker on the probability of occurrence of extreme wave crest heights are shown and discussed. Next a method for calibration of directional waves is presented. Finally, the modeling of deterministic waves in a model basin is dealt with.

Key words: Extreme waves, wave crest distributions, wave generation

1. Introduction

When non-linear or extreme wave modeling is considered with respect to ship stability research, the following related questions can be raised:

1. How often do extreme waves occur and how relevant are they,
2. What are their typical shape and kinematics,
3. How can extreme waves be generated in wave basins.

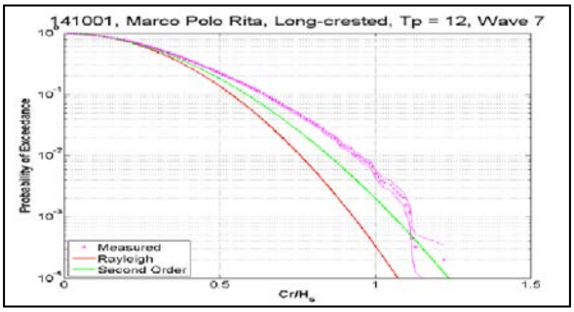
These questions shall be treated in the following, looking both at state-of-the-art methods and at recent research.

2. Probability of Occurrence and Relevance of Extreme Waves

From the numerous data sets investigated during the CresT JIP, a Joint Industry Project on the effect of extreme wave impacts on offshore structures, it was concluded that a second order wave crest distribution function is a good basis for the estimation of a design wave crest, see Ref [1]. However, depending on parameters such as directional spreading, sea state steepness and propagation distance, crests may exceed the second order distribution in severe seas by some 10%. On the other hand, the very highest crests may be limited by breaking and even fall below a second order model.

2.1 Effect of directional spreading

For three different sea states at the same peak period, the effect of spreading is illustrated in Fig. 1. Three spreading increases from top to bottom. The sea states were measured in the MARIN Offshore Basin during the CresT project. The waves were steep, with a nominal significant wave height of 12 m and a peak period of 12 seconds. The model scale was 50. The measured crest height distribution lies above both the Rayleigh distribution and the standard second order distribution (Ref [2]) for the long-crested and the low spreading case. The measurements show that the deviation from second order theory is much less in short-crested waves. It should be noted that the figures correspond to one seed per sea state. In ongoing projects, corresponding investigations concern a large number of seeds.



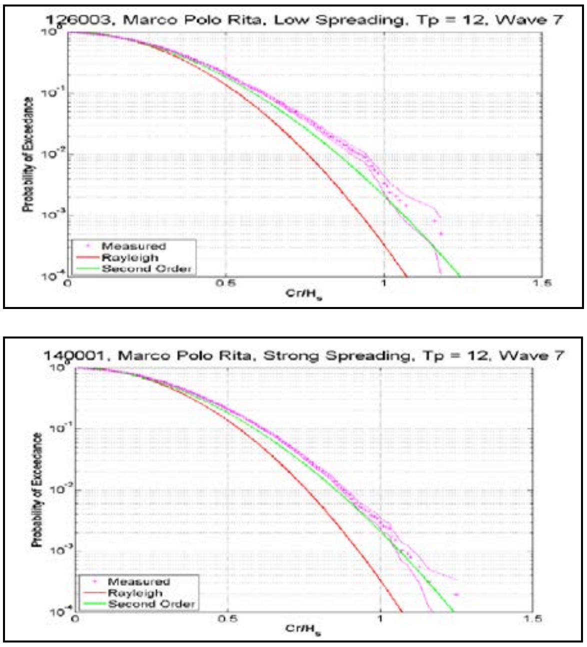


Figure 1 Wave crest distribution depending on spreading, from top to bottom: Long-crested, low spreading (s=15) and strong spreading (s=4).

2.2 Effect of sea state steepness

The effect of sea state steepness is illustrated in Fig. 2 (see also Ref [1]) showing the measured crest distributions for 4000 hours of field data. The steepness increases from top to bottom. The sea state steepness is defined on basis of the mean spectral period T_1:

$$S_1 = \frac{2\pi H_s}{g T_1^2} \tag{1}$$

It can be seen that the wave crests become higher with increasing sea state steepness, starting from below the second order theory and increasing up to a significant deviation beyond second order. For the largest crests, wave breaking as counteracting effect limits a further increase. This effect of wave breaking as a limiting process is considered an important observation.

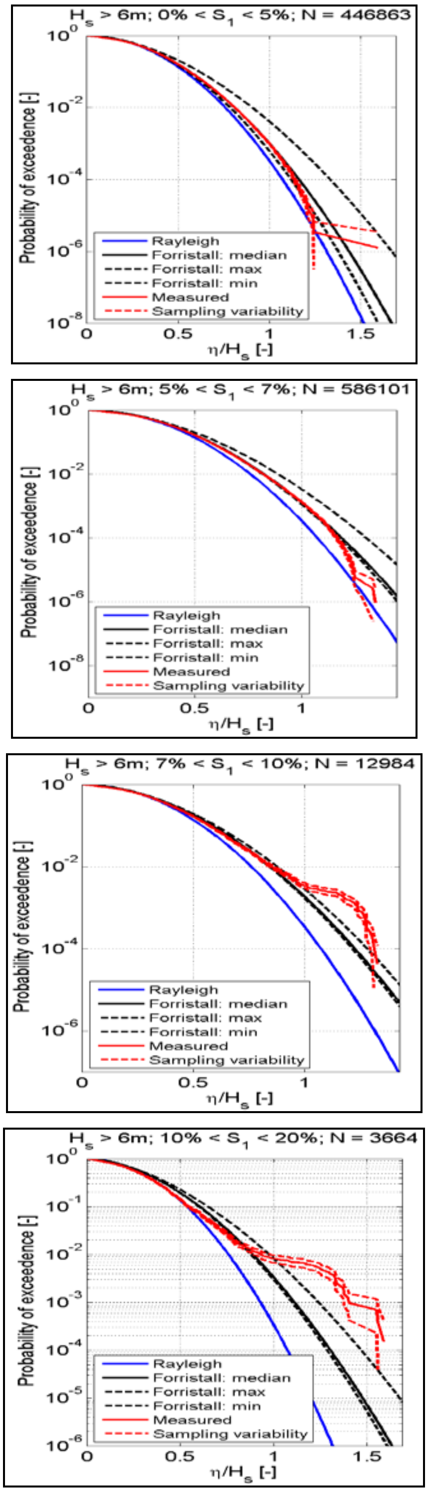


Figure 2 Wave crest distribution depending on sea state steepness, increasing from top to bottom.

2.3 Effect of distance (from the wave maker)

In order to investigate the effect of wave evolution with distance on the wave crest distributions, measurements at several locations along MARIN's Offshore Basin length were carried out. Fig. 3 shows the distribution of wave probes over the basin length.

Following the evolution of the wave with increasing distance from the wave generator, it can be observed that breaking does not stop the possible further development of extreme crests. Fig. 4 shows crest height distributions for the same test, but at greater distances from the wave generator. These measurements show that in long-crested waves it may take a few wave lengths to modify the crest height distribution. The observed growth may be due to third-order resonant interactions, or Benjamin-Feir instabilities, accompanied by a shift of spectral energy in frequency band and seems somewhat faster here than has been reported in some other studies – at scale 1:50, the MARIN Offshore Basin has a length of 5-10 wave lengths.

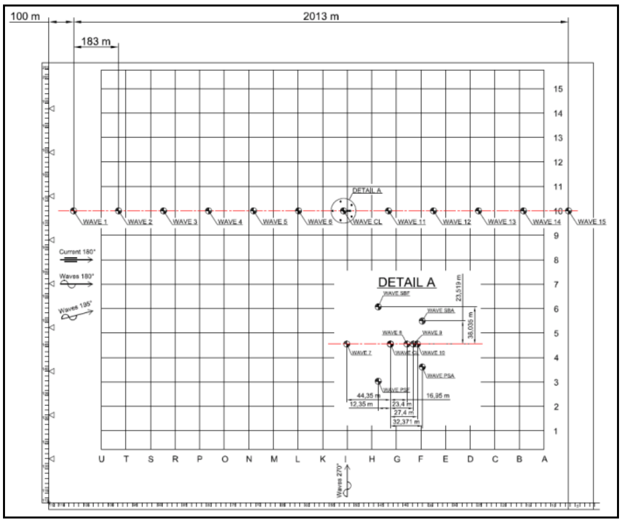


Figure 3 Distribution of wave probes along MARIN's Offshore Basin.

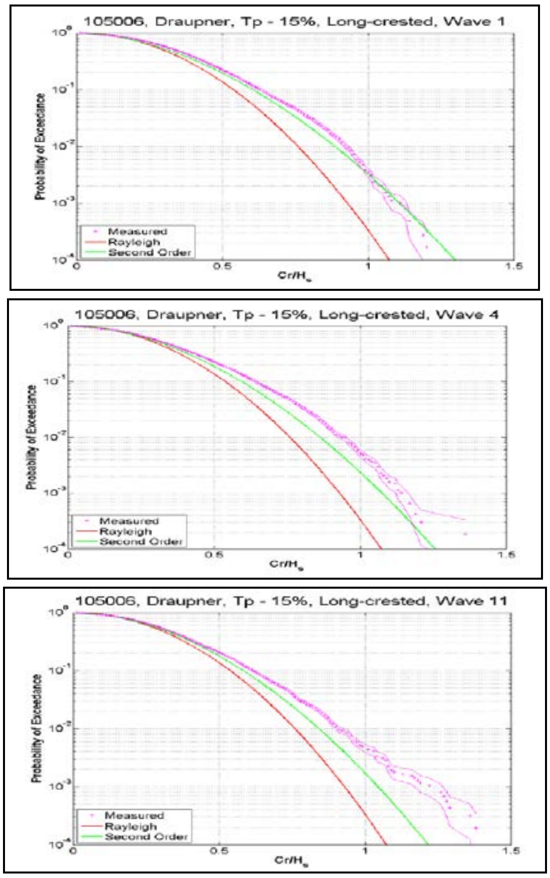


Figure 4 Crest height distribution observed for long-crested seas.

In summary, for the wave statistics, the following can be concluded from the research undertaken in CresT:

1. Use the Forristall distribution for the wave height.
2. Use the second order distribution as basis for the crest height.
3. Correct for observed deviations from second order. This is subject to ongoing research.

3. Calibration of Directional Waves

Understanding the processes described previously and giving useful recommendations demands an effort in defining the correct wave spectrum, understanding wave amplification and breaking, and generating fully non-linear crest statistics in a scheme useful for engineering application.

To improve the quality of the waves in a model basin a calibration loop can be used. For a target wave spectrum the wave maker control software determines the theoretical flap motions, leading to a wave realisation in the basin. Depending on the quality of the wave maker theory used, the resulting wave in the basin can differ from the target spectrum. In a typical calibration loop the generated wave is measured and analyzed. The resulting spectrum is compared against the target spectrum. Next the target spectrum sent to the wave maker can be adjusted in an attempt to obtain a better quality basin wave.

For long-crested waves the calibration procedure is well established and included in common wave generation software. For short-crested waves a similar approach was implemented and tested at MARIN. First the directional spectrum $S(\omega,\theta)$ is defined as a combination of a frequency dependent spectrum $S(\omega)$ and a frequency and direction dependent spreading function $D(\omega,\theta)$; in the correction procedure $S(\omega,\theta)$ and $D(\omega,\theta)$ are treated separately. In global overview the calibration works as follows:

1. Generate wave in the basin for the theoretical spectrum $St(\omega)$ and spreading function $Dt(\omega,\theta)$.
2. Measure and analyse the resulting realization to determine the measured spectrum $Sm(\omega)$ and measured spreading function $Dm(\omega,\theta)$.
3. Compute the corrections $CS(\omega)$ and $CD(\omega,\theta)$.
4. Generate a new wave attempt based on $CS(\omega).St(\omega)$ and $CD(\omega,\theta).Dt(\omega,\theta)$
5. Repeat from point 2 until satisfied.

To measure the waves, resistance type wave elevation probes are used. The probe layout consists of a number of small footprint arrays distributed over a larger area of the basin. To determine the wave spectral density, a mixture between two methods is used: EMLM (Extended Maximum Likelihood Method, see Ref [3] and MEM (Maximum Entropy Method, see Ref [4]) which are both implemented and tested for typical probe arrays. For the frequencies above 2.5 rad/s (18 s prototype) a slope based MEM method is used on each of the small footprint arrays to obtain local information on $Dm(\omega, \theta)$. At lower frequencies (longer waves) the slope falls within the resolution/measurement accuracy of the wave probes within a small footprint array. As an alternative a phase difference based EMLM method is used, based on single wave probes distributed over a larger area in the basin. Combining the two methods give a reliable analysis for a wide range of frequencies. The correction factor $CD(\omega,\theta)$ is computed using: $CD(\omega,\theta) = Dm(\omega,\theta)/Dt(\omega, \theta)$. The correction is only computed for the range of ω and θ values with sufficient spectral energy.

Fig. 5 shows the results of the directional wave calibration: Example for an Ewans' spread sea state calibrated in MARIN's Seakeeping and Manoeuvring Basin. Top left: Measured directional spectrum. Top right: Theoretical spectrum. Bottom figures: Directional distribution at a selection of frequencies

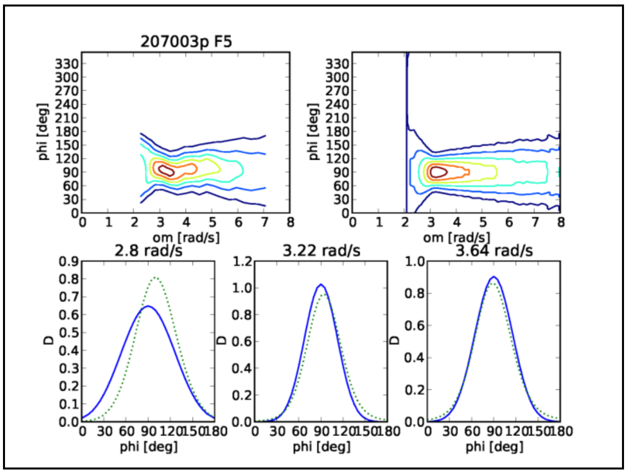


Figure 5 Example of directional wave calibration

4. Extreme wave modeling in model basins

To model extreme waves appropriately both in the basin and in numerical simulations, different approaches are required which are addressed briefly in the following sections.

4.1 Deterministic wave generation

Deterministic wave generation means to reproduce a predefined target wave train at a given position and time in a basin. For the generation of deterministic wave sequences in a model basin different types of wave makers are available. The wave generation process, as illustrated in Fig. 6 for the example of a double flap wave maker, can be divided into four steps:

1. Definition of the target wave train: the target position in time and space is selected – for example the position where a ship encounters the wave train at a given time. At this location, the target wave train is designed – based on defined parameters or a wave record.
2. Upstream transformation: the target wave train is transformed upstream to the position of the wave maker, e. g. by means of a non-linear wave propagation model.
3. Calculation of control signals: the corresponding control signals are calculated using adequate transfer functions of the wave generator.
4. Performing the model tests: the control signals are used to generate the specified wave train which is measured at selected positions in the tank.

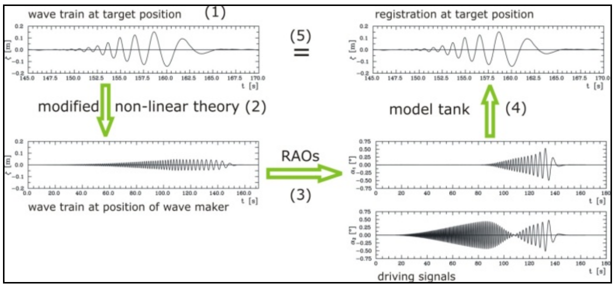


Figure 6 Process of deterministic wave generation

4.2 Optimization of wave realisations

Furthermore, the target wave can be achieved by optimization applied both to a numerical and a physical wave tank. In the figure below, for the example of the well-known "New Year Wave" as extreme directional wave, this optimization process is illustrated. The "New Year Wave" was measured on 01/01/95 in the Norwegian sector of the North Sea (Draupner) by a down-looking radar, see Ref [5]. It is a 20 min wave record, with T_P = 10.8 s, H_S = 11.92 m, H_{MAX} = 25.6 m ⇨ H_{MAX} / H_S = 2.15, Crest height 18.5 m, water depth = 70 m. The directional wave generation based on optimization works as follows:

1. Combining target wave train (time domain) and directional spectrum (frequency domain) to "fronts" as an unique parameter set of wave frequency, heading, amplitude and phase.
2. Upstream transformation of wave fronts using linear theory
3. Calculating motion of first wave board, then of neighboring boards
4. Generate, measure and analyse wave
5. Start optimization of wave board motions, based on comparison with target wave

Fig. 7 shows the result of the optimized basin realization of the short-crested New Year Wave.

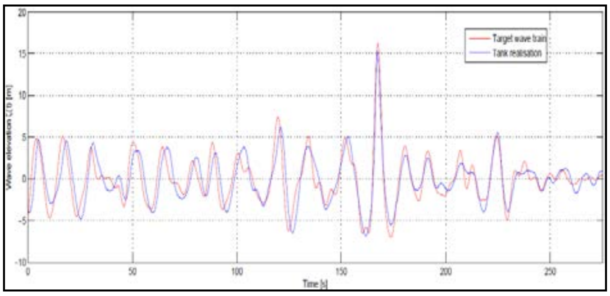


Figure 7 "New Year Wave".

5. Conclusions

The paper has shown that directional wave spreading reduces the probability of occurrence of extreme wave crest heights (for the same sea state steepness). Wave crests become higher with increasing sea state steepness, but wave breaking may reduce the crest height. However, wave breaking does not stop further development of extreme crests in downwind directions.

A calibration method for directional waves is discussed. Finally, the process used to generate deterministic waves in a model basin is discussed and an example is given.

Acknowledgments

The aim of this paper is to introduce the work of the ITTC Stability in Waves committee on the modelling of extreme waves. The present paper contains a chapter of the SiW report to the 27th ITTC in a rearranged format.

References

[1] B. Buchner, G. Forristall, K. Ewans, M. Christou and J. Hennig, "New Insights in Extreme Crest Height Distributions (A Summary of the Crest JIP)", Proceedings of OMAE 2011, Rotterdam, Netherlands.

[2] M. Provosto and G.Z. Forristall, "Statistics of Wave Crests from Models vs. Measurements", Proceedings of OMAE, Oslo Norway, 2002.

[3] O.J. Waals, A.B. Aalbers and J.A. Pinkster, " Maximum Likelihood Method as a Means to Estimate the Directional Wave Spectrum and the Mean Wave Drift Force on a Dynamically Positioned Vessel, 21st International Conference on Offshore Mechanics and Arctic Engineering, Oslo, Norway, 2002.

[4] M.J. Briggs, "Multichannel Maximum Entropy Method of Spectral Analysis Applied to Offshore Platforms", 14th Offshore Technology Conference OTC, Houston, TX, 1982.

[5] S. Haver, 'Evidences of Existence of Freak Waves', Rogue Waves Workshop, Vol. 1, 129-140, Brest, 2000