2- AND 3-DIMENSIONAL DETERMINISTIC FREAK WAVES

by

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1. ABSTRACT

The present paper deals with a new non-linear technique for generation of violent breaking freak waves (plunging breakers) at specified positions and times in wave basins. First, results concerning generation of non-linear wave trains, Stokes-waves and wave solitons in deep water are given. Then the technique for generation of non-linear wave transients are given with specified non-linear dispersion properties. Finally, the new techniques are used to obtain collisions between non-linear solitons coming both from the same direction (2-dimensional case), and from different directions (3-dimensional case) leading to generation of steep and violent plunging breakers.

2. INTRODUCTION

The amount of high violent breaking waves that is contained in a sea, is a most important factor to consider for design of both offshore structures, coastal structures and ships. Some critical events might happen just in certain kinds of steep extreme waves, but the same events do not happen in a normal sea state described and simulated in the laboratory by the use of the traditional wave spectrum. Stochastic simulations contain normally a low amount of breaking waves, and in most cases they do not contain extreme wave events, such as very high waves breaking as plunging breakers in deep waters. Further, the wave spectra might be identical for two wave simulations, one containing a very violent and dangerous freak wave leading to a critical event, the other not containing such a wave. Thus, use of a wave spectrum is not a complete and adequate description of a sea state and the effect it might have on structures. Finally, in stochastic simulations of irregular seas in the laboratory it is very often observed that the ratio between the maximum observed wave height and the significant wave height is too low. (The required ratio is 2 in most cases.)

An alternative technique for a fast, efficient and accurate determination of extreme responses and critical events that might occur at sea, is a new non-linear technique for generation of solitons that interact and break as very violent freak waves at a predetermined position and time in deep waters. The critical events that are under consideration here, are shown in Fig. 1.

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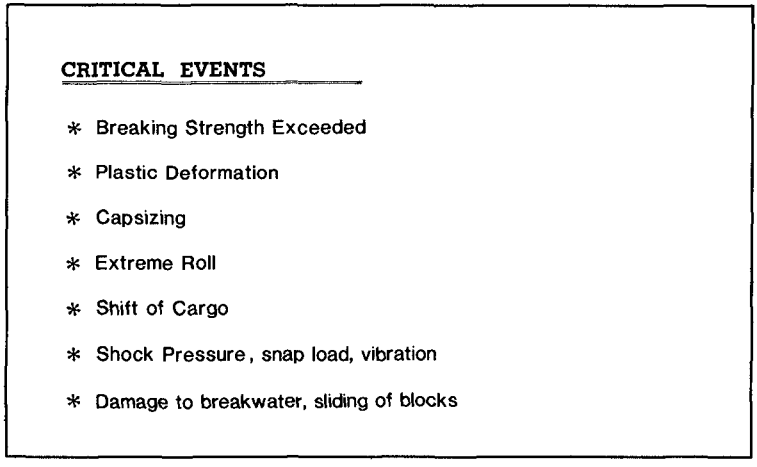

Fig. 1 Critical events.

Very often the designer has to investigate if such a critical event might happen or not. If the answer is yes, the designer then has to decide if such an event is acceptable or not. Very often he will then raise the question: "What is the probability for such an event?" If the probability is very low, he might then find that the conditions are acceptable. However, if the probability is high, he will often find that the conditions are not acceptable and he will develop a new design. Therefore, at the Norwegian Hydrodynamic Laboratories a new design philosophy is derived as follows:

1. Generate an extreme breaking freak wave in the laboratory.
2. Determine from wave statistics the statistical probability for occurrence of such a wave.
3. Measure the extreme response in an experiment.
4. Observe if a critical event occurs and repeat the experiment.
5. Give the probability for failure of the structure.

The procedure is shown graphically in Fig. 2.

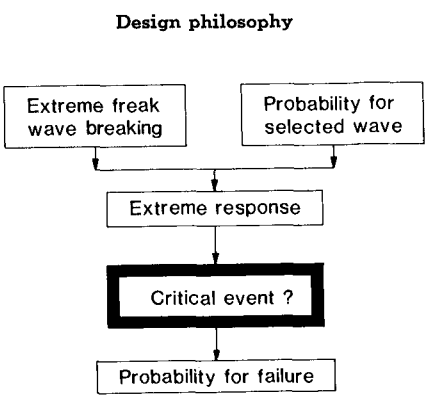

Fig. 2 Design philosophy.

This philosophy was first derived in a research programme "Ships in Rough Seas" (see publication from NSFI/RINA (1982)), but has now obtained much more international attention, and have recently been used in two projects performed for the offshore industry with experimental simulations performed at the Norwegian Hydrodynamic Laboratories. The same kind of philosophy might very well be applied to coastal structures. The present paper will only deal with the generation of extreme breaking freak waves in deep waters. Selection of design waves and probability calculations is given by Kjeldsen (1981).

3. STATE-OF-THE-ART IN WAVE GENERATION TECHNIQUES

In the following a brief summary of available wave generation techniques shall be given. Perfection of generation techniques for steady state longcrested, regular gravity waves (Stokes waves, cnoidal waves and sinusoidal waves) may be regarded as a first step in state-of-the-art of wave generation in hydrodynamic laboratories. The most interesting here is the non-linear generation techniques for Stokes waves in deep waters and cnoidal waves in shallow waters. However, it is also very well known that a sinusoidal command signal applied to a wave generator will not lead to generation of a sinusoidal wave train. Instead irregular waves are observed in the wave flume with the basic frequency superposed with freely travelling higher harmonics. Thus, the simple demand to reproduce a "clean" sinusoidal wave train in a wave flume without parasitic disturbances demands a laborous phase-compensating tehcnique, in which higher harmonics is supplied artificially in anti-phase with the unwanted parasitic noise. This technique is well known and described by Buhr Hansen, Schiolten & Svendsen (1975). The present paper will deal with the more complicated non-linear generation technique for generation of Stokes waves in deep waters.

The second step in state-of-the-art of wave generation techniques in laboratories is then the generation of a steady state stochastic sea containing irregular wave fields in 2- or 3-dimensions. The available techniques for generation of stochastic seas are all linear and are based on the use of Fourier analysis and one-dimensional or directional wave spectra. However, both the directional spectra for the 3-dimensional wave field, and the common frequency spectra for the 2-dimensional longcrested wave field must necessarily be truncated, due to the physical limitations in the frequency range that is present when a prescribed spectrum is simulated artificially with mechanical wave generators. In simulations of a directional spectrum the selection of the truncation parameter affects the magnitude of the spectral moments m_0, m_2 and m_4, and also the obtained crest lengths that

are achieved in the experiment (Kjeldsen & Price (1982)). Further, it is well documented that the frequency spacing in the spectral simulation is essential for correct reproduction of slow-drift phenomena. However, even the two-dimensional directional sea spectrum appears to be insufficient, for a proper description of sea states containing extreme waves, wave trains with sequences of breaking waves and wave groups. Several radically different time series have been found -some containing violent breaking freak waves or wave groups - others not, and all have the same wave spectrum (Johnson, Ploeg, Mansard (1978)). A quite high frequency both of damages to coastal and marine structures and of capsizings of smaller vessels that recently have been experienced in different parts of the world, suggest that state-of-the-art in selection of proper design waves or design spectra for various kinds of maritime structures is just not good enough (Baird et al. (1980), Bruun (1979), Nedrelid (1978), Stephens et al. (1981)).

With this background a third and more advanced step in wave generation techniques is under rapid development (Kjeldsen (1978), Funke & Mansard (1979), Takezawa (1981), Kjeldsen & Myrhaug (1980), Kjeldsen, Vinje, Myrhaug, Brevig (1980), Mansard, Funke, Barthel (1982)). These new techniques contain sequences of deterministic transient waves leading either to violent breaking freak waves or to formation of wave groups with specified characteristics, and these sequences might be included in a stochastic time series in such a way that a certain specified wave spectrum is matched. The present paper will deal with the following 2 subjects:

1) Description of development of a new non-linear experimental technique for deterministic generation of freak waves both in 2 dimensions (longcrested freak waves) and in a directional 3-dimensional shortcrested wave field.
2) Discuss various possible combinations of superposition of deterministic sequences containing wave transients, with stochastic time series as obtained in a 3-dimensional wave field.

Fig. 3 gives a summary of all available combinations.

Development of wave generation techniques for case no. 4, 8, 10 and 12 will be dealt with in the present paper and is therefore circled. Thus, in the following we shall concentrate on

case 4) Generation of non-linear steady-state wave trains.

case 8 & 10) Interaction and collisions between non-linear solitons in 2- and 3-dimensions.

case 12) A combination of the steady state stochastic simulation with the transient state deterministic simulation. This last case is linear because the stochastic directional sea is simulated using linear assumptions.

All the experiments and developments referred to in this study are performed at the Norwegian Hydrodynamic Laboratories in Trondheim, Norway.

Art of wave generation - steady state

1	Regular Sinusoidal Waves	Linear	Deep and shallow water
2	One-dimensional Spectrum	—	—
3	Directional Spectrum	—	—
(4)	Stokes Waves	Non-linear	Deep water
5	Cnoidal Waves	—	Shallow water

Art of wave generation - transient state

6	2-Dimensional Freak Wave	Linear	Shallow water
7	2-Dimensional Freak Wave	—	Deep water
(8)	2-Dimensional Freak Wave	Non-linear	—
9	3-Dimensional Freak Wave	Linear	—
(10)	3-Dimensional Freak Wave	Non-linear	—

Combined steady state/transient state

11	One-dimensional Spectrum with superposed Freak Wave	Linear	Deep Water
(12)	Directional Spectrum with superposed Freak Wave	—	—

Fig. 3 State-of-the-art in wave generation techniques.

4. GENERATION OF SOLITONS

The familiar non-linear Schrödinger equation (4.1) as first derived by Zakharov (1968) describes a wide variety of physical situations. Here, we shall limit the description of the theory to gravity water waves in deep water. The equation is:

$$i\left(\frac{\delta A}{\delta t} + \frac{\omega_o}{2k_o}\frac{\delta A}{\delta x}\right) - \frac{\omega_o}{8k_o^2}\cdot\frac{\delta^2 A}{\delta x^2}$$

$$- \frac{1}{2}\,\omega_o k_o^2 \cdot |A|^2 A = 0 \qquad (4.1)$$

Here, A is the complex envelope:

$$A = a \cdot e^{i\theta} \qquad (4.2)$$

and a is the physical amplitude.

According to the theory there exists a carrier wave number k_o and a corresponding cyclic frequency ω_o which remains constant throughout the evolution. Thus, variations in k can be described as deviations from the carrier wave number:

$$k = k_o + \Delta k \qquad (4.3)$$

The mathematical solution of eq. (4.1) relevant to deep water waves is given by Zakharov & Shabat (1972). Their main results are:

1) An initial wave envelope pulse of arbitrary shape will eventually disintegrate into a number of solitons and an oscillatory tail. The number and structure of these solitons and the structure of the tail are completely determined by the initial conditions.

2) Each soliton is defined as a permanent progressive wave solution to eq. (4.1) and has the form:

$$S_n = a_n \cdot \sec\sqrt{2}\,k_o^2 a_n \cdot \left[(x - \chi_n) - \left(\frac{\omega_o}{2k_o} + V_n\right)t\right] + \exp\left\{-\frac{i}{4}k_o^2 a_n^2 \omega_o t - \frac{4ik_o^2}{\omega_o}\cdot V_n\left[(x - \chi_n) - \left(\frac{\omega_o}{2k_o} + V_n\right)t + \theta_n\right]\right\} \qquad (4.4)$$

(Here, n is an index that refers to the n^{th} soliton. a_n is its amplitude and V_n is its velocity relative to the group velocity $\omega_o/2k_o$. χ_n and θ_n is its position and phase.)

3) Provided that wave breaking does not occur, the solitons are stable in the sense that they can survive collisions and interactions with each other with no permanent change except a possible shift in position and phase.

4) The remaining tail is relatively small and unimportant for a pulse initial condition. It disperses linearly resulting in a $1/\sqrt{t}$ decay of the amplitude.

Experiments with monochromatic steep non-linear wave trains were carried out in a 78 m long wind-wave flume at the Norwegian Hydrodynamic Laboratories. It was found that it was possible to use a sinusoidal command signal and a wave flap hinged at the bottom to produce highly non-linear solitons that dispersed in well controlled transient experiments with phase velocities and group velocities that exceeded predictions made from linear theory. Also a tail was observed behind the solitons that dispersed linearly. Further, it was found that the dispersion velocities for the obtained solitons agreed very well with numerical results given by Cokelet (1977) for high order Stokes waves.

With this knowledge a series of very well controlled experiments were then carried out in which two monochromatic steep non-linear wave trains with different frequencies were generated at different times. This was performed in such a way that two solitons were brought into interaction with each other at a position 60 m from the wave generator. This resulted in the generation of a violent plunging breaker in deep water obtained as a result of a collision between only two solitons.

An example of such an experiment is given by Kjeldsen, Vinje, Myrhaug & Brevig (1980) (Fig. 5, page 323 and Fig. 9, page 325). A large summary report containing all performed experiments will also be available Kjeldsen (1983).

5. THEORETICAL STORM MODEL

In the following a new theoretical model for travelling of wave transients with non-linear dispersion properties shall be derived. We introduce the operator:

$$\Lambda(\omega) = e^{-j\omega / \omega \sqrt{\frac{x}{g}} \frac{1}{\kappa}} \tag{5.1}$$

Λ is a frequency response function for non-linear waves that relates wave heights measured at two points separated by a distance x in the direction of travel. ω is the cyclic frequency, g is the gravity acceleration, while κ is a non-linear dispersion factor depending on wave steepness. As shown in section 6 the produced waves are solitons with a synoptic shape that shows a high degree of coherence with Stokes waves as calculated by Cokelet (1977) (using Padé approximants with series expansions to the order ε^{110}). Thus, for the non-linear wave transients under consideration here Cokelet's results are very good approximations. Fig. 4 shows κ as a function of wave steepness.

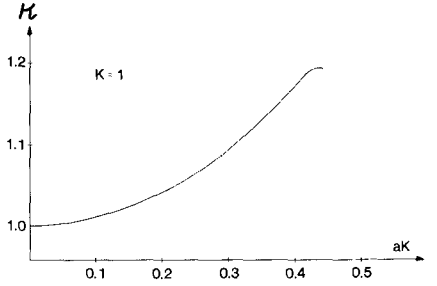

Fig. 4 Wave dispersion factor as a function of wave steepness $\left(a \cdot K = \frac{H}{L} \cdot \pi\right)$ (From Cokelet (1977)).

For non-linear waves we now introduce a "unit impulse response function" λ defined by the transformation:

$$\lambda(\tau) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \Lambda(\omega) \cdot e^{j\omega\tau} \cdot \frac{1}{\kappa}\, d\omega \tag{5.2}$$

The unit impulse response function λ represents a convenient method of determining the response $q(t)$ to an input of any form $Q(t)$ through the method of Duhamel's convolution integral:

$$q(t) = \int_{-\infty}^{\infty} \lambda(\tau) \cdot Q(t-\tau)\, d\tau \tag{5.3}$$

Substituting eq. (5.1) into eq. (5.2) gives:

$$\lambda(\tau) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-j\omega/\omega\sqrt{\frac{x}{g}}\cdot\frac{1}{\kappa}} \cdot e^{j\omega\tau}\,\frac{1}{\kappa}\, d\omega \tag{5.4}$$

introducing trigonometric terms we obtain:

$$\lambda(\tau) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \cos\left(\omega^2\frac{x}{g}\frac{1}{\kappa} - \omega\tau\right) d\omega$$

$$+\frac{i}{2\pi}\int_{-\infty}^{\infty} \sin\left(\omega\tau - \frac{\omega^2 x}{g}\frac{1}{\kappa}\right) d\omega \tag{5.5}$$

By use of the symmetry relations we finally obtain:

$$\lambda(\tau) = \frac{1}{\pi}\int_{0}^{\infty} \cos\left(\omega^2\frac{x}{g}\frac{1}{\kappa} - \omega\tau\right) d\omega \tag{5.6}$$

We now consider non-linear waves of constant steepness κ.

We introduce the substitutions:

$$\xi = \frac{x^{1/2}}{g^{1/2}} \cdot \frac{1}{\kappa^{1/2}}\left(\omega - \frac{g\tau}{2x}\right) \tag{5.7}$$

$$\frac{d\xi}{d\omega} = \frac{x^{1/2}}{g^{1/2}}\,\frac{1}{\kappa^{1/2}} \tag{5.8}$$

and:

$$\sigma = \frac{g^{1/2}\cdot\tau}{2x^{1/2}\cdot\kappa^{1/2}} \tag{5.9}$$

We then obtain:

$$\lambda(\tau) = \frac{1}{\pi}\frac{\kappa^{1/2}\cdot g^{1/2}}{x^{1/2}}\int_{-\sigma}^{\infty} \cos(\xi^2 - \sigma^2)\, d\xi \tag{5.10}$$

and:

$$\lambda(\tau) = \frac{1}{\pi}\,\frac{g^{1/2}\cdot\kappa^{1/2}}{x^{1/2}}\left\{\cos\sigma^2\left[\int_{-\sigma}^{0}\cos\xi^2\,d\xi + \int_{0}^{\infty}\cos\xi^2\,d\xi\right] + \sin\sigma^2\left[\int_{-\sigma}^{0}\sin\xi^2\,d\xi + \int_{0}^{\infty}\sin\xi^2\,d\xi\right]\right\} \tag{5.11}$$

We can now recognise the well known relations for Fresnel's integrals:

$$\int_0^\infty \sin\xi^2\,d\xi = \int_0^\infty \cos\xi^2\,d\xi = \frac{1}{2}\sqrt{\frac{\pi}{2}} \tag{5.12}$$

and:

$$C(\mu) = \int_0^\mu \cos\left(\tfrac{1}{2}\,\pi\,\mu^2\right)d\mu \tag{5.13}$$

$$S(\mu) = \int_0^\mu \sin\left(\tfrac{1}{2}\,\pi\mu^2\right)d\mu \tag{5.14}$$

Substitution then gives:

$$\lambda(\tau) = \left(\frac{g\,\kappa}{2\pi x}\right)^{1/2}\left\{\left[\cos\sigma^2\right]\cdot\left[\frac{1}{2} + \frac{\sigma}{|\sigma|}\cdot C\left(\sqrt{\frac{2}{\pi}}\,\sigma\right)\right] + \left[\sin\sigma^2\right]\cdot\left[\frac{1}{2} + \frac{\sigma}{|\sigma|}\,S\left(\sqrt{\frac{2}{\pi}}\,\sigma\right)\right]\right\} \tag{5.15}$$

We now introduce a new parameter:

$$b = \left(\frac{\kappa\cdot g}{2\pi x}\right)^{1/2} \tag{5.16}$$

Eq. (5.9) then gives:

$$\sigma = \sqrt{\frac{\pi}{2}}\cdot\frac{b\,\tau}{\kappa} \tag{5.17}$$

and we finally obtain:

$$\lambda\left(\frac{b\,\tau}{\kappa}\right) = b\left\{\left[\cos\frac{\pi}{2}\,\frac{b^2\tau^2}{\kappa^2}\right]\cdot\left[\frac{1}{2} + \frac{\tau}{|\tau|}\,C\left(\frac{b\,\tau}{\kappa}\right)\right] + \left[\sin\frac{\pi}{2}\,\frac{b^2\tau^2}{\kappa^2}\right]\cdot\left[\frac{1}{2} + \frac{\tau}{|\tau|}\,S\left(\frac{b\,\tau}{\kappa}\right)\right]\right\} \tag{5.18}$$

This is thus the final expression for the "unit impulse response function" λ, expressed with Fresnel's integrals which are functions of the dimensionless time parameter $b \cdot \tau / \kappa$ that governs the non-linear interactions.

The freak wave is now approximated with the Dirac-function defined by:

$$\delta(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{i\omega t} \, d\omega \tag{5.19}$$

This function has the properties:

$$\delta(t) = 0 \quad \text{if } t \neq 0 \tag{5.20}$$

$$\int_{-\infty}^{\infty} \delta(t) \, dt = 1 \tag{5.21}$$

$$\int_{t_1}^{t_2} q(t) \quad \delta(t-t_o) \, dt = \begin{cases} q(t_o) & \text{if } t_1 < t_o \leq t_2 \\ o & \text{otherwise} \end{cases} \tag{5.22}$$

(Eq.(5.22) is valid if q(t) is continuous at t_o and t_1, t_2 are constants with $t_2 > t_1$) If index 1 refers to the position of wave generation and index 2 refers to the position of the freak wave, then the time history at position 1 is given by Duhamel's integral eq. (5.3) as:

$$\eta(x_1, t) = \int_{-\infty}^{\infty} \lambda(\tau) \cdot \eta(x_2, t - \tau) \, d\tau \tag{5.23}$$

This can also be expressed as:

$$\eta(x_1, t) = \Lambda(\omega) \cdot \eta(x_2, t) \tag{5.24}$$

Eqs. (5.23) and (5.24) are the time domain equivalents of:

$$N(x_2, \omega) = \Lambda(\omega) \cdot N(x_1, \omega) \tag{5.25}$$

where N is the transform of the time histories obtained as:

$$N(x, \omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \eta(x, t) \cdot e^{-i\omega t \frac{1}{\kappa}} \, dt \tag{5.26}$$

The freak wave at position 2 is now approximated with a Dirac-function and we have:

$$\eta(x_2, t) = \delta(t) \tag{5.27}$$

Then

$$N(x_2, \omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \eta(x_2, t) \, e^{-i\omega t \frac{1}{\kappa}} \, dt = \frac{1}{2\pi} \tag{5.28}$$

and

$$N(x_1, \omega) = \frac{1}{2\pi} \Lambda^{-1}(\omega) \tag{5.29}$$

The inverse transform is then obtained as:

$$\eta(x_1, t) = \int_{-\infty}^{\infty} N(x_1, \omega)\, e^{i\omega t \frac{1}{\kappa}}\, d\omega \tag{5.30}$$

or:

$$\eta(x_1, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-i\{\omega^2 \frac{x}{g} \frac{1}{\kappa}) - \omega t\}}\, d\omega \tag{5.31}$$

or:

$$\eta(x_1, t) = \frac{1}{\pi} \int_{0}^{\infty} \cos(\frac{\omega^2 x}{g} \frac{1}{\kappa} - \omega t)\, d\omega \tag{5.32}$$

Eq. (5.32) is identical with eq. (5.6) and it is thus shown that the unit impulse response function λ represents the time series $\eta(x_1, t)$ at position 1. Eq. (5.18) can then be used directly to produce a command signal for the wave generator. For large values of σ, we obtain the simplification:

$$C(\mu) = S(\mu) \simeq \frac{1}{2} \tag{5.33}$$

and

$$\lambda(\tau) = \sqrt{2}\, b \cos(\frac{\pi}{2} \frac{b^2 \tau^2}{\kappa^2} - \frac{\pi}{4}) \tag{5.34}$$

Thus, we have obtained an extension and non-linear modification of a technique for linear transient waves described by Davis & Zarnick (1964).

6. DEVELOPMENT OF COMMAND SIGNALS FOR 2-DIMENSIONAL FREAK WAVES

The theoretical storm model given in section 5 can now be directly used to develop command signals for wave generators. Thus, eq. (5.18) or eq. (5.34) can be directly used to prepare analog signals for wave generators. Since 1977 experiments of this kind have been performed at the Norwegian Hydrodynamic Laboratories in 3 different wave flumes, first one 33 m long, 1 m wide and 1.6 m deep, second one 78 m long, 4 m wide and 1.6 m deep, and the third one 280 m long, 10 m wide and 10 m deep, all equipped with flap-type wave generators. Fig. 5 gives an example of such an experiment performed in the third wave flume. A large plunging breaker with a wave height 0.74 m is generated 41 m from the wave generator and 66 seconds after the start of the transient signal.

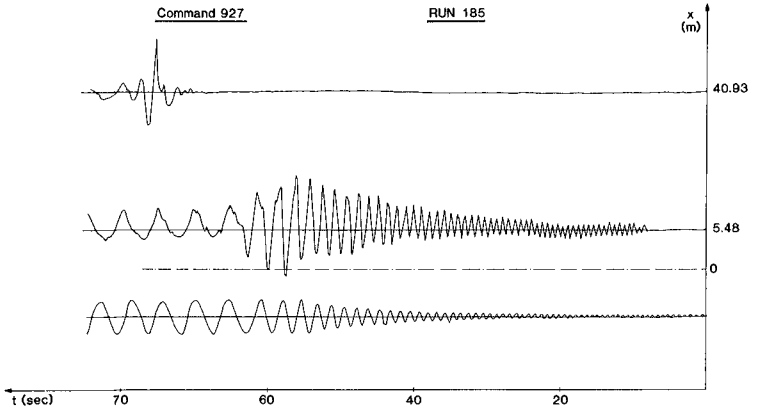

Fig. 5 Deep water plunging breaker generated from an interaction of 43 single wave components. The command signal to the wave generator is shown at the bottom.

It is most important to consider the fact that the analytical model developed in section 5 for dispersion of storm waves makes the assumption that all generated wave components have the same steepness. Thus, κ becomes a constant. To achieve this eq. (5.18) or eq. (5.34) has to be multiplied by a correction factor, that is an increasing function of time. With such a correction analog signals were prepared for the wave maker. At the wave maker waves were generated with a constant initial steepness 0.10, starting at a frequency 2 Hz. In this way the final plunging breaker obtained as a result of the collision of the 43 wave components was very close to the maximum that might be achieved. Fig. 6 shows results from 11 repeated experiments of this kind. Measured parameters are trough-to-crest wave height H_{zd}, zero-downcross wave period T_{zd}, horizontal asymmetry factor μ defined as the ratio between crest height and wave height, and finally crest front steepness ε_t (defined in Kjeldsen & Myrhaug (1980)). For each parameter both the mean value and the standard deviation σ are shown. From this result compared to 16 mm high speed film recordings of the plunging breaker, we conclude that the repetition in the generated freak waves is very high. Fig. 7 shows a non-dimensional plot of synoptic wave shape where experimental obtained values were compared with Cokelet's results for high order Stokes waves with the same steepness. $\varepsilon^2 = 0.70$ is Cokelet's expansion parameter.

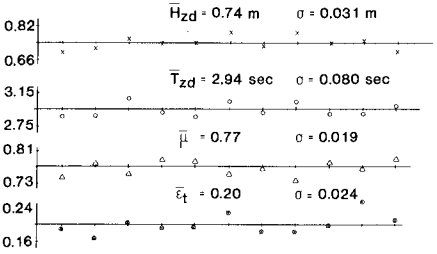

Fig. 6 Control of repetition in experiments.

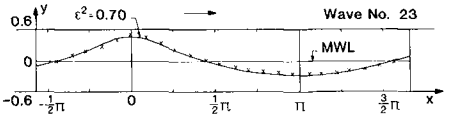

Fig. 7 Non-dimensional synoptic comparison of experimental wave component No. 23 at x = 5.5 m and Cokelet's results for high order Stokes waves.

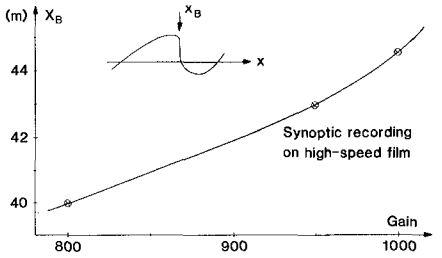

Fig. 8 Non-linear transfer of breaking point as a result of increase in gain on analog signal to wave generator.

The experimental wave component (No. 23) shown in Fig. 5 and measured at 5.5 m is converted from time domain to synoptic domain using equations given by Cokelet (1977, page 210). A coherence between experimental values and Cokelet's results is observed with steep wave crests and flat troughs. This is remarkable because Cokelet's results refer to a steady state condition, while the experiment is a highly transient condition. Thus, we take the observed coherence as a confirmation of the soliton theory used here. Finally, Fig. 8 shows a comparison between 3 identical transient tests with the same analog command signal but with a different gain on the wave maker. The positions x_B where the wave fronts become vertical are recorded and measured on high speed film and shown on the figure. Thus, when the gain is changed from 800 to 1000 the plunging breaker is shifted downwards in the wave flume from x_B = 40 m to x_B = 44.3 m. This is a true non-linear behaviour. Dispersion velocities of all wave components increase with increasing amplitude, and the experimental technique and control are advanced enough to keep the wave focusing properties. Thus, this new non-linear experimental technique can be used to finally adjust a violent plunging breaker to give a very direct strike on a test structure placed for instance 42 m from the point of wave generation.

7. DEVELOPMENT OF COMMAND SIGNALS FOR 3-DIMENSIONAL FREAK WAVES

The same technique was also extended to 3-dimensions. Experiments were carried out in the new ocean basin at the Norwegian Hydrodynamic Laboratories. The basin is 80 m long, 50 m wide and 10 m deep. At the 80 m long side 144 individually controlled single flap type wave generators are installed in an array. Each flap is a "Belofram" sealed membrane hinged 1.02 m below mean water level. At the other sides are efficient energy absorbing parabolic beaches. 144 different command signals of the same type as described in section 5 were prepared for these wave generators in such a way that focusing of wave energy would take place from many directions simultaneously resulting in a large pyramidal breaking wave close to the far end of the basin 40 m from the wave generators. Fig. 9 shows a very steep shortcrested breaking wave (pyramidal breaker) obtained at sea, while Fig. 10 shows a reproduction of the same situation in the ocean basin. The general conclusion from these tests is that non-linear effects in steep waves changed directional propagation and amplified energy focusing. Further, the small flap generators produced linear waves from linear command signals. Thus, it was not possible to generate non-linear solitons as described in section 5. (The wave maker used for the experiments shown in Fig. 5 is a large flap hinged 2.6 m below mean water level.) However, extreme non-linear waves were obtained in the end in the ocean basin as a result of the wave focusing, as can be seen in Fig. 10, but this was first obtained after a non-linear adjustment of wave phases. Finally, some experiments were carried out in which large freak waves were superposed at a certain time on a given directional spectrum using linear theory. However, this leads in all cases to spilling breakers and no plunging breakers were obtained in this way. A 16 mm film showing 3-dimensional experiments were shown at the conference. Further details on these experiments are given by Kjeldsen (1983).

Fig. 9 A dangerous wave captured at sea by Fukumi Kuriyama, Nikkor Club, Nippon, Kogaku, K.K. Japan.

Fig. 10 Reproduction of a pyramidal breaker at the ocean basin.

8. CONCLUSIONS

1) Linear wave theory failed to predict the experiments. Instead an analytical theory is developed that takes into account the observed non-linear dispersion of wave solitons. Command signals for generation of freak waves can thus be obtained as modified versions of equations (5.18) and (5.34).
2) Close to breaking individual wave components can no longer be regarded as travelling independently of each other. Instead, wave-wave interactions take place leading directly to generation of violent plunging breakers in deep waters.
3) The final amplitude of the obtained freak waves cannot be found as a sum of individual wave components measured close to the point of wave generation. A more complicated physical process determines the maximum amplitude where onset of wave breaking is the upper frame.
4) Transient non-breaking wave shapes can be generated with steepnesses that significantly exceed the theoretical value 0.14 for limiting steepness of steady state non-linear waves.
5) Application of this new non-linear transient wave generation technique showed the following advantages:

a) In most conventional tests performed with various structures in deep water plunging breakers are absent. In many conventional tests the total amount of breaking waves (spilling breakers, plunging breakers and bores) is too low. If a plunging breaker occasionally occurs in a simulated stochastic sea "by chance", it is nearly always out of the test section and far away from the structure under investigation. The transient test technique, however, can locate a most violent plunging breaker at a predetermined time and space that strikes exactly at the structure and repeats with great accuracy.

b) Both the total amount of breaking waves and the different types of breaking waves are main factors to consider in simulated seas. The amount of plunging breakers in simulated seas might determine if a critical event takes place or not (i.e. exceeding of breaking strength, capsizing of vessel). The transient deterministic test technique has been developed far enough to excitate resonance and amplify certain dangerous frequencies in a non-linear coupling. After establishment of a resonance a violent plunging breaker strikes the structure as the last wave in a long wave train.

c) The obtained 3-dimensional extreme waves represent a close approximation of the maximum wave height that might be obtained in a given directional wave spectrum with the physical restrictions and all the non-linear effects from wave interaction present. Thus, it represents an alternative choice, to the 100-year design wave obtained from an often uncertain mathematical extrapolation of limited field data from a short period of years.

d) Scale effects can be reduced because higher wave amplitudes and higher Keulegan-Carpenter numbers can be achieved. Conventional use of wave makers leads to lower wave amplitudes and larger scale effects.

e) Transient tests are more accurate than conventional test techniques. The deterministic transient tests can be programmed and planned in such a way that unwanted noise and parasitic disturbances on the responses can be avoided. The parasitic disturbances considered here are unwanted higher harmonics generated by the mechanical wave generators and unwanted reflections from beaches and flume walls. For this reason the transient test technique is a most efficient method to obtain the frequency transfer functions for responses of various structures in waves.

f) Application of transient deterministic test technique for mapping of extreme responses, means much more efficiency in the laboratory and lower costs, due to the fact that the extreme situation can be repeated with great accuracy many times in a single day of testing. On the other hand, conventional test programs for structures in deep waters very often have a long test period and in many cases not a single strike is obtained directly on the structure from a plunging breaker.

6) It was found that traditional stochastic experiments using wave spectra can be directly misleading in some cases. Stochastic experiments and transient experiments were performed on the same structure and the same maximum wave height was expected. However, the trough to crest oscillation in a measured mooring force became twice as high in the transient experiment compared to the stochastic experiment. Thus, conventional test methods give results that are on the non-conservative side in some cases and might lead to a severe underestimation of the wave forces the oceans are able to create.

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