DIRECT SIMULATION OF FREAK WAVES FOR EXTREME DESIGN CONDITIONS

Antonio CARDO, Riccardo CODIGLIA, Giorgio CONTENTO and **Fabrizio D'ESTE**

DINMA - Department of Naval Architecture, Ocean and Environmental Engineering, University of Trieste
Via Valerio, 10 – 34127 TRIESTE, ITALY
Phone: +39-040-6763424 Fax: +39-040-6763443 e-mail: contento@univ.trieste.it

SUMMARY

This paper describes some recent results obtained at DINMA on the nonlinear behaviour of large unidirectional waves in the presence of frequency focusing. The study is conducted by means of direct numerical simulations in the frame of the inviscid fluid hypothesis. It is shown that given for a given spectrum generated by a wavemaker in a closed basin the nonlinear wave-wave interaction can give a large magnification of the crest elevation if compared to the traditional linear superposition. This is found to be due to the implicit generation of high frequency components. Moreover the phase speeds of the input components exhibit a slight increment and the new frequency component travel with the same speed of the smallest wave of the given spectrum.. Finally the numerical results obtained are compared with laboratory data showing extremely similar characteristics.

INTRODUCTION

"... Loss of a large norwegian ship with the entire crew in the middle of the North Atlantic is not a common event. However at a special occasion two large norwegian bulk ships M/S NORSE VARIANT and M/S ANITA disappeared at the same time at the same location…. Both ships came right into the center of a very extreme weather event with a strong low pressure giving 15 m significant wave heights and mean wave periods close to 10 seconds … with wind velocities near 60 knots. NORSE VARIANT had deck cargo that was damaged and moved by water on deck with the result that a hatch cover was broken and left open. This ship took in large amounts of water and sank before an organised evacuation was finished. Only one member of the crew was rescued on a float. ANITA disappeared completely at sea with the whole crew and no emergency call was ever given.

The Court of Inquiry then concluded that the loss can be explained by an event in which very large wave suddenly broke several hatch covers on deck, and the ship was filled with water and sank before any emergency call was given. …"

On the same stream of the previous indirect witness of the presence of extremely large single waves in rough seas [*Kjeldsen*, 1], *Clauss* [2] suggests that the loss of the semisubmersible OCEAN RANGER could have been due to a single large wave, since weather reports from all the neighbouring platforms in the same geographic area do not mention evident anomalies in the sea state.

On the other hand, evidences given by measurements of the presence of such waves are becoming more and more frequent. Figure 1 (courtesy of Prof. Ove Gudmestad – STATOIL, Norway) shows the wave elevation measured on January 1 1995 at Daupner station. The significant wave height is 11.9 m approximately and the max wave height detected in the time series is approx. 25.5 m, with a crest height 18.5 m above the still sea level.

It is well known that since the early 50's the predictions of loads on fixed offshore structures and motions of compliant or sailing structures due to surface waves are commonly made by computations on the basis of the statistical/spectral description of the sea elevation.

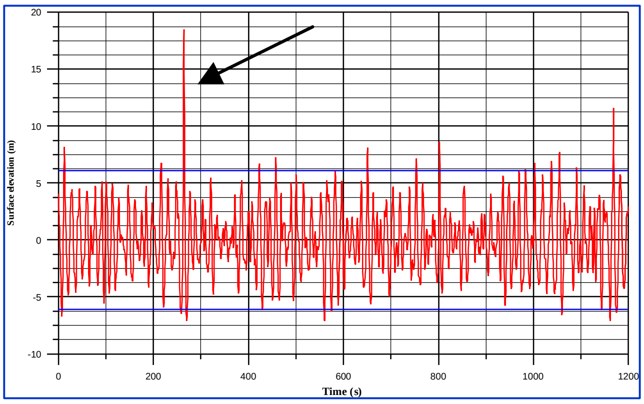

Figure 1. Wave elevation at the Daupner station on January 1 1995 (courtesy of Prof. Ove Gudmestad).

This approach, based on the linear wave model, is now an almost common procedure and it has been recognised that it works reasonably well for the so-called "operational" conditions. The advantages related to the assumption of linearity are enormous and the method is widely accepted.

On the other hand, it is also recognised that the predictions in the so-called "survival" conditions, i.e. extreme wave conditions with very low occurrence probability, cannot recast a linear approach. In particular it may happen that the maximum elevation of the components within the relevant part of the sea spectrum are almost in phase at a specific location leading to the so-called "freak" wave.

From the structural point of view and specifically for the fatigue life, the transit of a freak wave, even not breaking, at the location of a vertical pile (Gravity Based Structures) or an array of floating cylinders (Tension Leg Platforms), can cause the dangerous ringing phenomenon, i.e. the large amplification in few cycles of the response of the structure at its natural frequency. This happens even if the frequency region of the spectrum where most of the energy is concentrated is well below the natural frequency of the structure. Chaplin [3] has related by lab. experiments the occurrence of ringing with the time interval between the zero-downcrossing after the freak wave crest and the next zero-upcrossing. In the same context, Chaplin [3] has shown that focused component waves behave in a fully non-linear manner in a relatively small region around the concentration point. In his experiments the maximum wave elevation is underestimated by linear predictions by 10% approximately, a non negligible amount of energy is (not permanently) shifted to the high frequency range, well above the input spectrum, and at these new frequency components the phase speed shows an almost constant value.

Large single waves are usually strongly asymmetric. Myrhaug and Kjeldsen [4] report that " … in the same time series measured at sea the maximum wave height could deviate with 25%, depending on the choice of analysis, i.e. zero-upcrossing or zero-downcrossing analysis". Such a difference is explained in terms of strong asymmetry of the freak wave profile.

The aim of the research conducted at DINMA on large single waves in a random sea is to investigate the non-linear effects that derive from the interaction of the component waves when focusing occurs, i.e. when or where the phase between them is close to zero. A deeper knowledge of the behaviour of the flow in such extreme conditions can be extremely useful for design purposes also related to safety aspects. Moreover the controlled generation of deterministic wave groups with a given frequency content, aimed at the development of new techniques for seakeeping tests, is one of the subjects of interest in the *23rd ITTC*.

MATHEMATICAL MODEL AND NUMERICAL METHOD IN SYNTHESIS

The details of the mathematical model and of the numerical method employed for the simulations have been widely described in [5-6] so that only a synthesis is given here.

With reference to Figure 2 and according to the assumptions that the fluid is incompressible and inviscid and the flow is irrotational, the velocity potential $\phi(x,y,t)$ yields on *D*. The continuity equation can thus be written as an integral equation

$$\int_{\partial D} \frac{\partial G(\boldsymbol{P},\boldsymbol{Q})}{\partial n}\phi(\boldsymbol{Q})ds - \int_{\partial D} G(\boldsymbol{P},\boldsymbol{Q})\frac{\partial \phi(\boldsymbol{Q})}{\partial n}ds = -\Omega(\boldsymbol{P})\phi(\boldsymbol{P})$$

The free surface profile is assumed single valued $y = \eta(x,t)$ and the fully nonlinear free surface conditions on it become

$$\begin{cases} \dfrac{d\phi}{dt} = -\dfrac{1}{2}(\nabla\phi)^2 - g\eta + \dfrac{\partial\phi}{\partial y}\left(\dfrac{\partial\phi}{\partial y} - \dfrac{\partial\phi}{\partial x}\cdot\dfrac{\partial\eta}{\partial x}\right) - \nu(x)\cdot\phi \\ \dfrac{d\eta}{dt} = \dfrac{\partial\phi}{\partial y} - \dfrac{\partial\phi}{\partial x}\cdot\dfrac{\partial\eta}{\partial x} - \nu(x)\cdot\eta \end{cases}$$

where $\nu(x)$ is the damping factor used at the numerical beach.

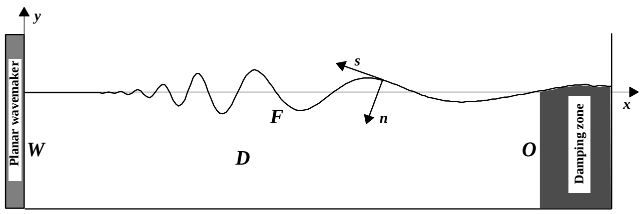

Figure 2. Schematic representation of a numerical 2D wave tank.

As far as the numerical scheme is concerned, Green's equation appropriately modified to include the symmetry condition given by the flat bottom of the tank, is solved by a constant panel method. The time stepping scheme is a 4th order Runge-Kutta method and regridding without smoothing is applied on the whole boundary.

WAVEMAKER MOTION FOR WAVE FOCUSING

Wave-wave interaction at focusing is a strongly nonlinear phenomenon. This mainly regards the dispersion relation, the phase speed and the wave amplitude. Moreover new component waves appear from the interaction of the input frequencies. These nonlinear phenomena have been shown by lab experiments [2, 7-9] and will be highlighted by the results presented here.

The departure from the linear behaviour of the input wave components must be taken into account in the wavemaker control signal since linear wave theory can give inaccurate estimates of the phase speed [3]: a phase shift is systematically observed in the simulations, the largest one occurring at the highest frequencies in the input spectrum.

In this study, linear theory is used for a preliminary estimate of the wavemaker driving signal. The time series at the focusing station is then analysed by means of an FFT and the phase lag detected (it should be zero for perfect focusing!) is used at the wavemaker in a further run. The procedure is repeated until the desired convergence is achieved. In the following this procedure is referred as “phase lag refinement”. Furthermore the position of the focusing station in the flume and the start-up time of each frequency component is selected in order to get a useful space and time window at focusing without beach reflections and evanescent modes induced by the wavemaker [10]. Details of this iterative method can be found in [5].

RESULTS

In the following reference is made to the shortest wavelength in the adopted spectrum. The results presented refer to $N_{freq} = 34$ different input frequencies w_i equally spaced in the nondimensional range $\frac{24}{57} \le \omega_i \le 1, \quad i = 1, N_{freq}$, the wave basin is 80 wavelengths long and the relative depth is $d = 0.525$. The focusing station is at $\hat{x} = 12$.

The amplitude spectrum used is such that the steepness of each input wave is always the same and no breaking occurs; it results $\left(\frac{H}{\lambda}\right)_i = \frac{1}{715}$. Figure 3 shows the amplitudes α_{0_i} of the frequency components of the angular motion of a flap wavemaker with rotation axis at the bottom of the tank .

Fig. 4 shows the contour plot of the amplitude spectrum of the wave elevation as a function of the coordinate x along the tank and of the frequency ω. *x* is varied in the range $7 \le x \le 27$. Fig. 5 shows the intersection of the surface given in Fig. 4 at the focusing station $x = \hat{x} = 12$. It can be seen that the effect of the nonlinear wave-wave interaction on the space variation of the amplitude spectrum results in an almost smooth shift of the energy towards the high frequency range ($\omega > 1$) for $x \le \hat{x}$ whereas an opposite behaviour appears after focusing for $x \ge \hat{x}$. This means that new high frequency components are generated by the focusing process in a relatively small region. This result is strongly supported by experimental ones obtained by Chaplin [3] and shown in Fig. 6. Moreover a non negligible and stable amount of energy can be observed in Fig. 4 for $x > 12$ in the low frequency range, clearly shown even in Fig. 5. It must be observed that the first seiching mode of the basin occurs at a very low nondimensional frequency *w*=0.0014.

This has been observed also by Tick [11], who developed a perturbative model for random waves. He used a Neumann-type spectrum with a 6 power dependence. His results show that the second order correction to the frequency spectrum exhibits a peak located at approximately twice the frequency of the first order peak and moreover a low frequency contribution appears at frequencies well below the first order spectrum.

Further aspects about the nonlinearities involved can be derived from Fig. 7 where the wave profiles at focusing from the linear and nonlinear simulation, with and without phase lag refinement, are reported. Both wave crests from nonlinear simulations exceed the maximum elevation of the linear wave by a factor 1.3 approx. and the wave profile without phase lag refinement shows an evident vertical asymmetry with a greater slope on the front side with the peak located at a greater distance from the wavemaker.

Finally, the phase speed of the component waves has been computed at the stations $x = 10$, $x = \hat{x} = 12$ (focusing) and $x = 14$ respectively. Fig. 8a-c show the computed nondimensional results (phase speed divided by the linear phase speed of the shortest wave component in the input band) as a function of frequency ω (dots). Solid lines represent the linear phase speeds *C*, 0.5*C* and *2C* respectively. From these graphs it can be clearly seen that away from focusing at $x = 10$, $x = 14$ and within the input frequency range the wave celerity behaves in good accordance with linear theory whereas the higher order wave components travel according to the nonlinear effects. At focusing and within input frequency range the celerity is slightly above the linear prediction and the higher order wave components have an almost constant phase speed. This means that the imposed coalescence of in-phase wave components makes the main features of the resulting freak wave dominant in almost the whole spectrum. A similar behaviour has been clearly observed in the experiments by Chaplin [3] shown in Fig. 9. His results derive from time series obtained linking 16 different time series in order to detect intermediate frequencies, if any. His analysis shows that most of the energy content is restricted to the input frequencies and their multiple.

CONCLUSIONS

In this study some effects of the interaction between wave components in a given spectrum have been analysed in the frame of the so-called fully nonlinear numerical wave tank approach. The basic features of the wave interaction for the test case here studied can be summarised in an amplification by a factor 1.3 of the wave height compared to the linear superposition with $\frac{H_{focus}}{H_{1/3}} \approx 3.3$, in a space variation of the spectrum around the focusing station with a non-permanent energy shift in the high frequency range and a more stable energy shift in the low frequency range. Furthermore the strong wave grouping at focusing leads to a slightly higher phase speed within the input range and an almost constant value at higher frequencies. Most of the conclusions here derived are well supported by similar results obtained on an experimental basis.

ACKNOWLEDGEMENTS

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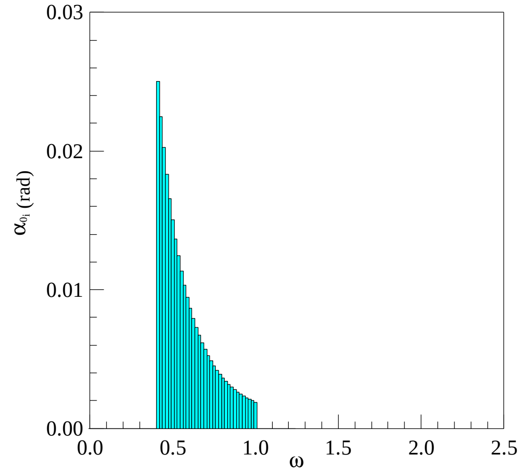


Figure 3 - Amplitudes of the frequency components of the motion of the flap-wavemaker.

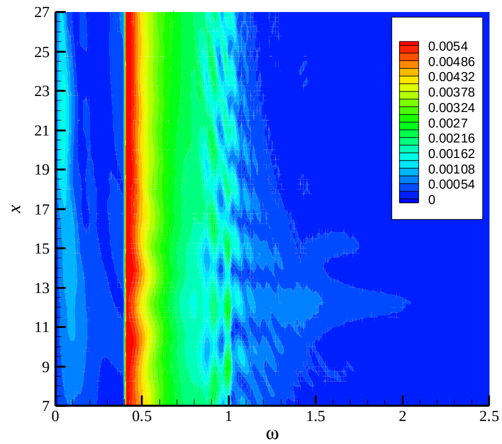


Figure 4 - Contour plot of the amplitude spectrum of the wave elevation as a function of the space coordinate *x* and of the frequency *w*. The focusing station is $\hat{x} = 12$.

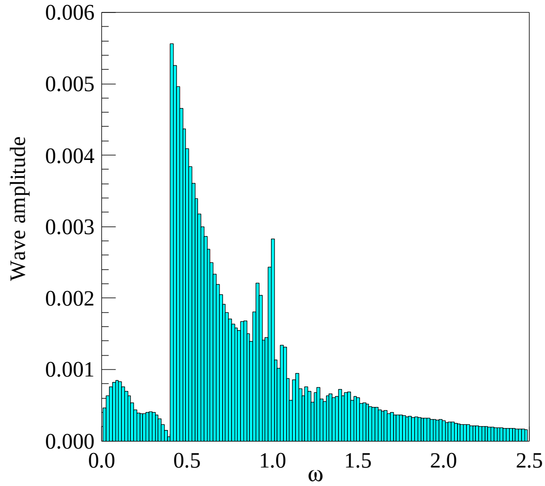


Figure 5 - Amplitude spectrum of the wave elevation at the focusing station $\hat{x} = 12$.

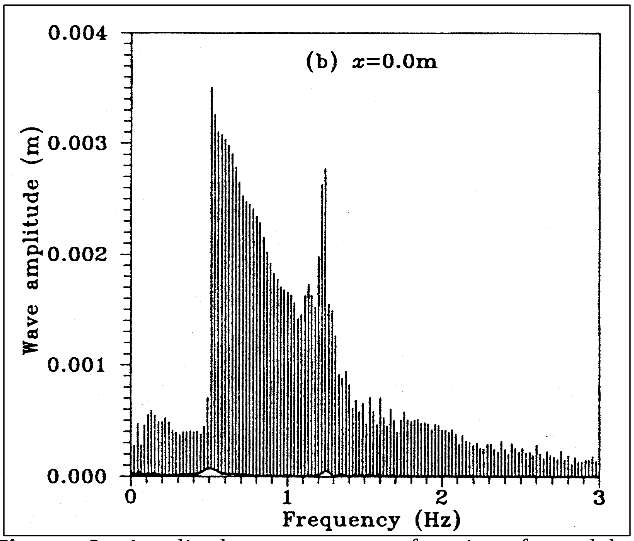


Figure 6. Amplitude spectrum at focusing from lab. experiments [Chaplin, 3].

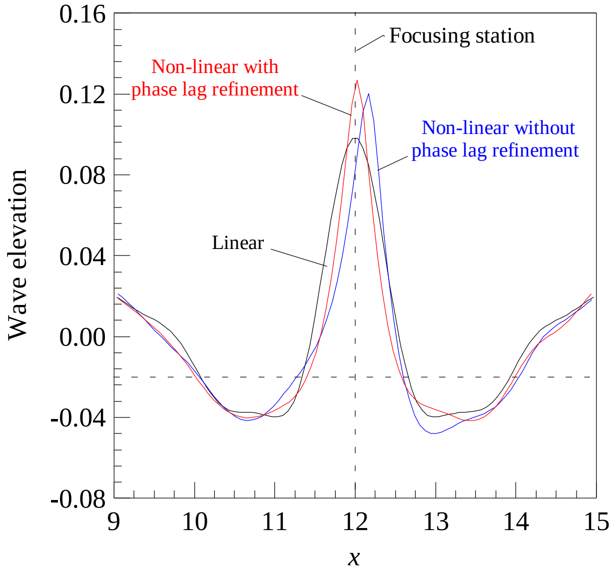
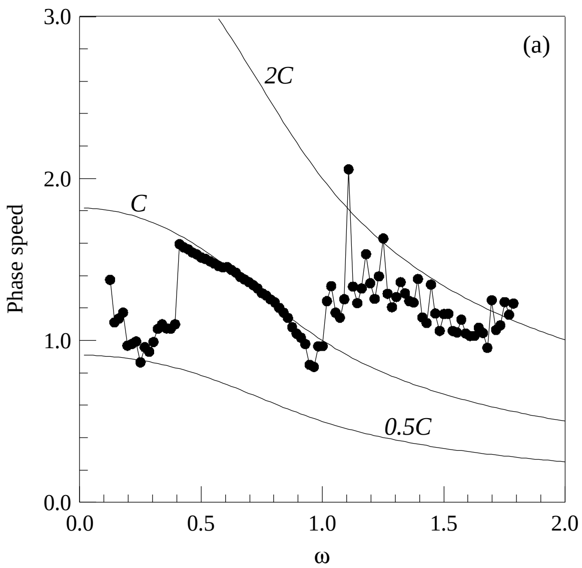
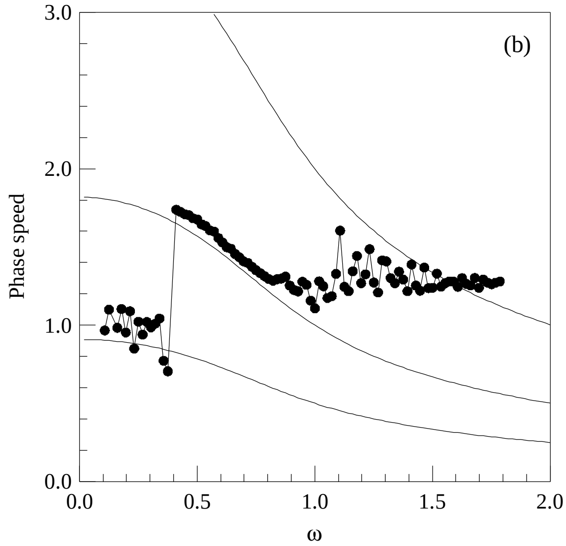


Figure 7. Wave profiles from linear (black) and nonlinear with (red) and without (blu) phase lag refinement.





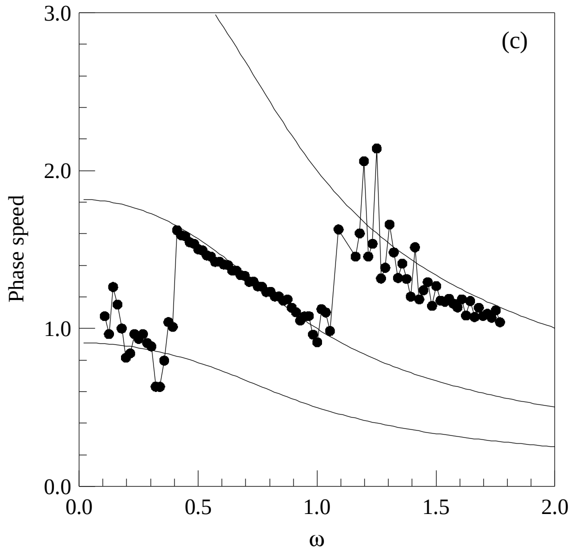


Figure 8a-c. Phase speed as a function of frequency at $x = 10$ (a), $x = \hat{x} = 12$ (b) and $x = 14$ (c). Solid lines represent the linear phase speed *C*, 0.5*C* and *2C* respectively

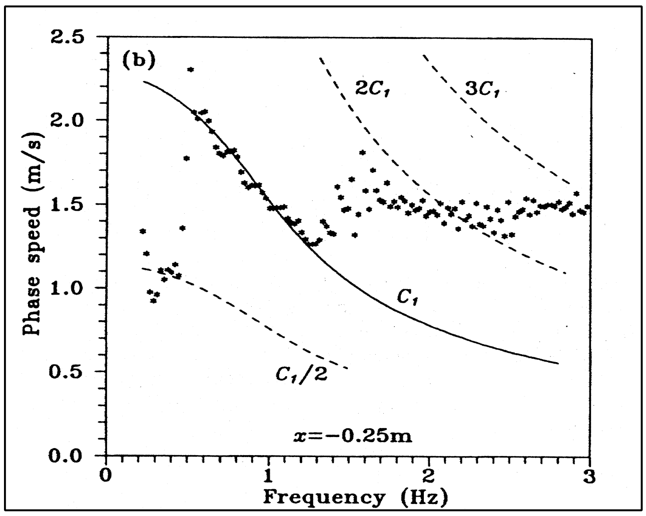


Figure 9. Phase speed at focusing as a function of frequency [Chaplin, 3].