98-242

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NWRI Contribution # 98-242

NATIONAL WATER RESEARCH INSTITUTE
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98-242

MANAGEMENT PERSPECTIVE

Title: **Velocities and Accelerations in Breaking Waves**

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NWRI Publication No.: 98-242

Citation: Proc. 8th (1998) International Offshore and Polar Engineering Conference, Montreal, 24-29 May 1998.

EC Priority /Issue: Accidental release of polluting substances threatening health and safety. Prevent the frequency/severity and environmental consequences of emergencies - ship capsizing and resulting spills.

Current Status: The occurrence of unusually large waves on the Great Lakes and on the oceans is a major factor in safety and pollution prevention (The sinking of Edmund Fitzgerald on Lake Superior and the sinking of the Ocean Ranger off Newfoundland are two examples where safety was compromised by large waves). These are waves larger than normally predicted using typical operational methods. There are two technical issues. When do they occur and how big are they? Can the internal water velocities and accelerations (and hence the forces on ships and offshore structures) be adequately described with present models so that ships and offshore structures can be safely designed? It turns out that existing models are not adequate. As a result of laboratory tests at NWRI and IRPHE in Marseilles during 1994-7, a more complete description of the kinematics has been made. A new model has also been developed which better predicts the internal velocities under the crests of these unusually large waves. This work was funded in part by a travel grant from NATO, contract no. 930137.

Next Steps: This paper will be presented at the International Offshore and Polar Engineering Conference in Montreal in 1998. A companion paper will be presented at the International Conference on Coastal Engineering in Copenhagen in 1998. The work is being refined and will submitted for journal publication to make the appropriate professional community aware of the improved modelling capability.

ABSTRACT

The unexpected occurrence of unusually large waves has been documented on numerous occasions. While little is known about the statistics of these waves, even less is known of the dynamical conditions under which they occur. Non-linear interactions among individual waves travelling within a group have been identified as an important mechanism in the formation of giant waves in the ocean. In this study, the non-linear packet focusing technique is used to generate steep, plunging waves in a laboratory flume. The kinematics of these waves are measured just up-wave of the onset of plunging and these results are compared to those of a superposition model, a modified stretching model, and a model based on Stokes 3rd order developed for the present study. The present model represents the velocity beneath the plunging breakers better than the two other models.

ISOPE-98
Montréal

8th (1998) International
OFFSHORE AND POLAR ENGINEERING CONFERENCE
Montréal, Canada, May 24-29, 1998

VELOCITIES AND ACCELERATIONS IN BREAKING WAVES.

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Abstract. The unexpected occurrence of unusully large waves has been documented on numerous occasions. While little is known about the statistics of these waves, even less is known of the dynamical conditions under which they occur. Nonlinear interactions among individual waves travelling within a group have been identified as an important mechanism in the formation of giant waves in the ocean. In this study, the non-linear packet-focusing technique is used to generate steep, plunging waves in a laboratory flume. The kinematics of these waves are measured just up-wave of the onset of plunging, and these results are compared to those of a superposition model, a modified stretching model, and a model based on Stokes 3rd order developed for the present study. The present model represents the velocity beneath the plunging breakers significantly better than the two other models.

Key Words: Wave kinematics, extreme waves, ringing effect, wave forces, wave accelerations.

1. Introduction.

Breaking waves play an essential role in air-sea interactions, and in assesment of impact loads on both fixed and floating coastal structures, platforms and ships see Kjeldsen (1997). Further breaking waves are very important for mixing and spreading of oil pollution in the upper surface layers of the sea.The dynamic action of the crest of a plunging breaker thus becomes particular important. Even now when theoretical and numerical treatments of the breaking problem have progressed, controlled experimental measurements for development and calibration of numerical ocean basins are needed. The present investigation reports synoptic measurements and analysis of particle accelerations and velocities of plunging crests in deep water wave groups. Further a third order simulation technique is developed in order to predict wave kinematics in extreme waves.

2. Experiments.

One series of experiments was performed in the large (40 m long 2.60 m wide) Air-Sea Interaction Simulation Facility of the I.O.A. laboratory of the I.R.P.H.E. Institute, located in Marseille. The wave generation technique developed by Kjeldsen (1982) was used for production of plunging breaking crests in deep water wave groups. A visualization technique, Bonmarin (1989), makes the wave profile visible and an associated image analysis process allows measurements of both the water surface geometry, crest front steepness and assymmetry (IAHR/PIANC 1986), as well as detailed measurements of accelerations of tracer particles dragged away by breaking and broken waves, see Fig. 1. and Fig. 3. Ten experiments designated by the reference of A11 to A21 were performed.
Another series of experiments was performed in the large wave tank at the Canada Centre for Inland Waters. The tank dimensions are 100 m in length, 4.5 m in width and the water depth for all runs were 1 m. Just upwave of the breaking wave, the water surface elevation was measured with a surface piercing capacitance wave staff, and the velocity was measured with an acoustic Doppler current meter. Replicate tests were performed to measure the velocity at various depths beneath the surface. See Skafel et al. (1997).

3. Results.

A Lagrangian measurement technique is needed in order to measure particle accelerations accurately in non-linear waves, see Lonquet-Higgins (1986.) In order to develop such a technique the wave-following properties of the tracer particles were mapped.
A calibration experiment was performed with a symmetric regular wave with steepness $ak = 0.31$. Fig 2 shows the measured trajectory, and a theoretical trajectory predicted by second order wave theory. A significant Stokes drift in agreement with the theory was obtained. This relative good agreement between experiment and theory validates the choice of the floating particles.
In the breaking waves the different steps of the measurements were i) the reconstruction of the trajectory of the floating particles (see Fig 4),ii) measurements of their celerity, and iii) the measurement of their acceleration, these two last measurements being deduced from the trajectory. Fig 5 shows an example of measured horizontal velocities of particles P1, P2, P3 and P4, shown in the experiment as it develops in Fig. 3. The horizontal velocities are normalized with the wave phase velocity c. Particle 4 reaches a horizontal velocity equal to the wave phase velocity, as it can be seen. Fig 6 then shows measured horizontal accelerations of the particles P2, P3 and P4, normalized with the gravity acceleration. The horizontal acceleration of particle P4 reaches a value of 1.55 times the gravity acceleration. Fig 7 shows the vertical acceleration of the particles P2,P3 and P4. Particle P3 reaches a value 0.78 times the gravity acceleration. The acceleration of the floating particles increases rapidly in the

non-breaking region and reaches a maximum value at the time when the overturning part of the crest collides with them (see Fig 5). Total acceleration vectors up to 1.5 g were measured at the free surface. Maximum acceleration and maximum velocity are nearly in phase in these breaking waves, leading to large wave forces, and a significant capzising potential if encounter happens with small floating objects (small boats, rescue floats or wave buoys). Kinematics in the interior of the plunging breakers were also measured with an acoustic doppler current meter, see Skafel, Drennan and Kjeldsen (1997).

If wave forces are computed on structural elements of a steel jacket or a tension leg platform then both the particel velocity and the acceleration must be known, and data presented here can be used for such computations. Wave particle accelerations in non-linear waves can not easily be deduced from Eulerian measurements. The wave crests shows an asymmetrical shape at the breaking onset, and work is in progress to establish a correlation between surface particle accelerations and wave asymmetry (see Kjeldsen, Bonmarin & Duchemin 1998)

4. Kinematic Models.

In the offshore industry a stretching theory developed by Wheeler (1970) has traditionally been used for prediction of kinematics of irregular sea states. In this study, we use a modified stretching model (Lo and Dean (1986) as representative of this class of model. (Donelan et al. (1992) report that it produces velocities very similar to the Wheeler method). We also used the superposition method proposed by Donelan et al. (1992), based on the linear superposition of a sum of freely propagating wave trains. Even when adapted to account for a possible mean flow, these linear models do not adequately represent the velocity beneath thecoalescing wave group.

In the present study we therefore developed a third order simulation of the kinematics in steep wave crests, see Skafel, Drennan and Kjeldsen (1997). This third order simulation technique is based on a combination of two earlier models. The first of these was developed by Kishida and Sobey (1988) and simulates a Stokes third order wave train on a current with a linear profile. This model is then used both for cases where non-linear waves propagate on opposing currents, and for cases without currents. However this model does not give a complete description of the wave spectrum developed by the command signal in the wave flume. Therefore the superposition model developed by Donelan et al. (1992) is also used. The procedure for computation then becomes:

1. A third order wave train interacting with a current with a constant vorticity is computed.
2. The third order wave train is subtracted from the experimentally obtained surface elevation.
3. The kinematics of the remaining wave signal is analysed using the superposition model of Donelan et al. (1992).
4. Finally the solutions obtained in steps 1) and 3) above are added, using the surface of the non-linear wave as mean water level for the additional wave components, in agreement with the concept behind the development of Donelan et al. (1992).

5. Model Comparison.

The mean predicted velocity profiles beneath the crests using the modified stretching model, the superposition model, and the present third order model are shown in Fig. 8 along with the experimental laboratory profiles. All the kinematic models were run for the surface elevation time series of all the laboratory runs (26 experiments with the same condition). The resulting mean profiles, along with twice the standard deviations about the means are plotted. The narrowness of the spread of the standard deviations presented in the figure serves as an indication of the excellent reproducability of the wave trains. Fourier analysis of each surface profile was used to find the peak frequency, and hence the peak wave number k_0. The mean peak wave number for all 26 runs, in this case $k_0=1.38\ m^{-1}$, was used for normalisation. It can be seen here that the modified stretching model underpredicts the velocity significantly throughout the profile. The superposition model more nearly represents the data. The new third order model developed here best reproduces the data. It slightly underestimates the velocity, lying just outside the two standard deviation range.

6. Conclusions.

1. The present third order kinematic model represents the velocity beneath extreme waves better than the modified stretching model and the linear superposition model.
2. A Lagrangian measurement technique is needed in order to measure particle accelerations in non-linear waves. By means of visualisation it was possible to measure the Lagrangian particle accelerations in breaking wave crests.
3. Both horizontal and vertical acceleration were measured. Total particle accelerations up to 1.5 g were measured in plunging breakers occurring in deep water.

7. Acknowledgement.

This work was supported in part by NATO, Scientific Affairs Division within the research programme on «Giant Waves caused by Wave-Wave and Wave-current Interaction.» under contract no. 930137.

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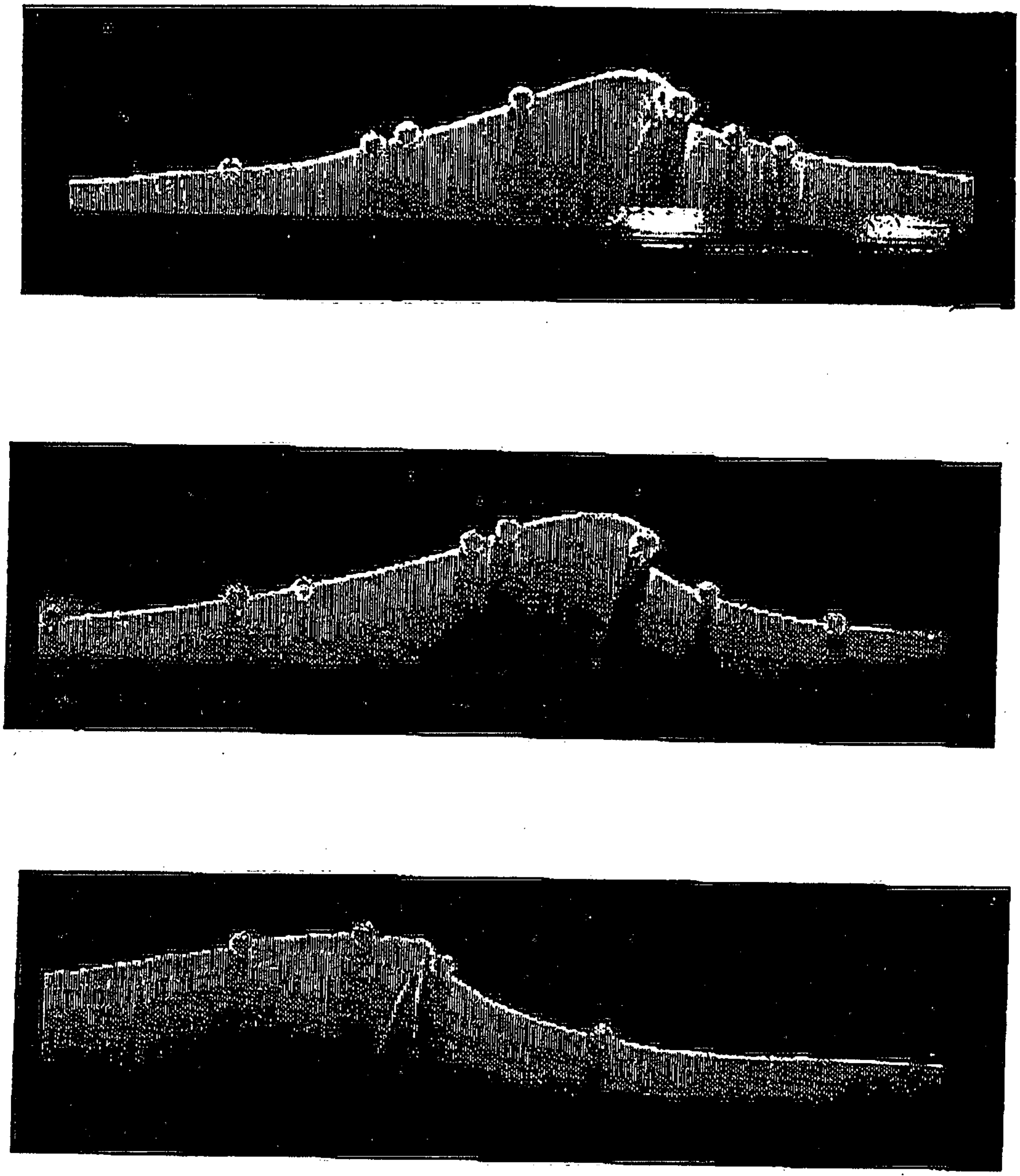

Figure 1. Sample of video pictures showing floating particles colliding with plunging crests.
Frame n° 29747(1) (top), 27142(2) (middle), 31549(1) (down).

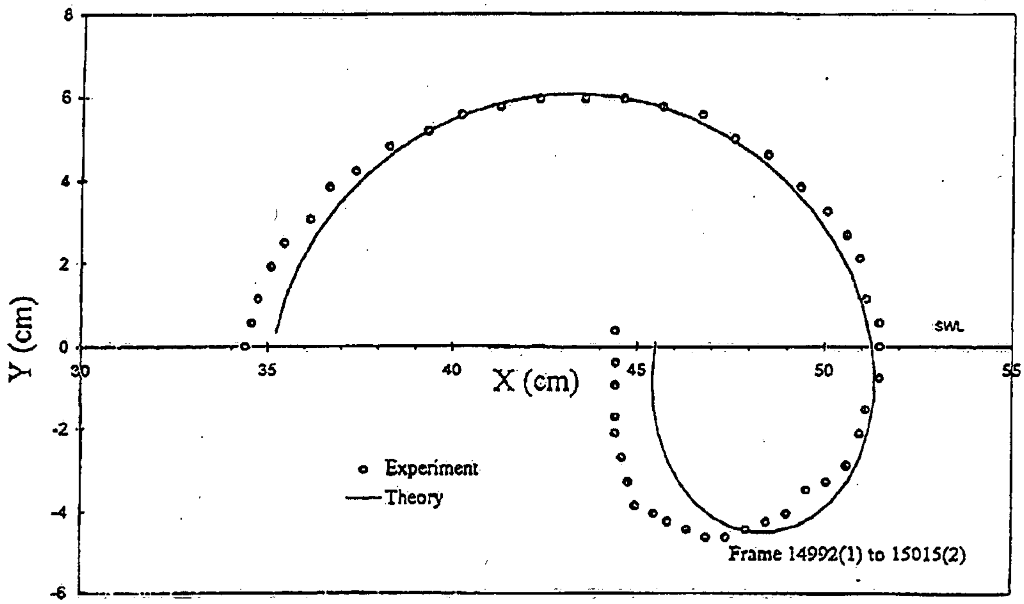

Fig. 2. Trajectory of a floating particle moving on a quasi symmetrical crest

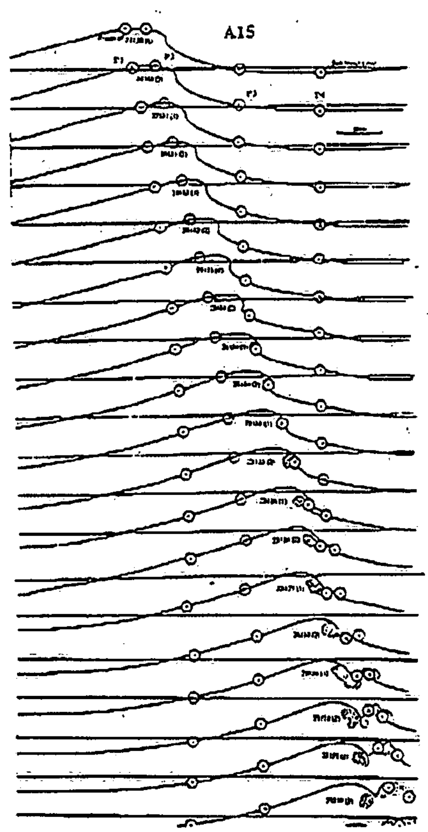

Fig. 3. Time Series for experiment A15. Frame period 0.02 sec.

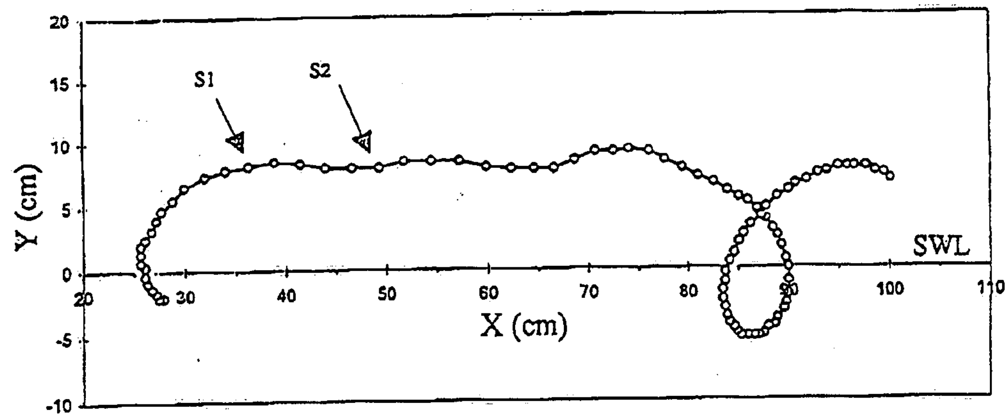

Fig. 4. Trajectory of a floating paticle colliding with a breaking crest. Experiment A14.

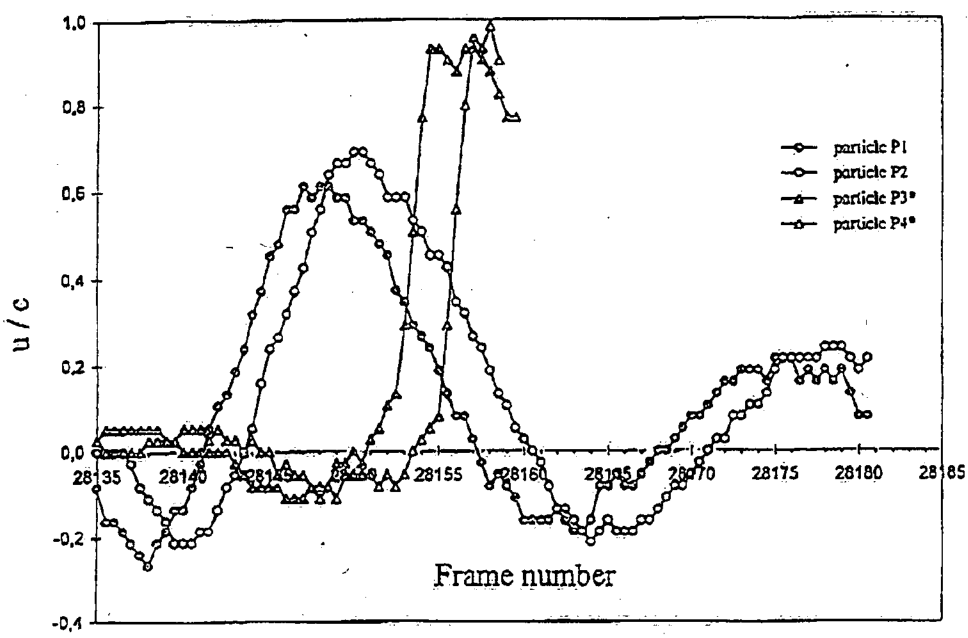

Fig. 5. Horizontal velocity of floating particles. Experiment A15.

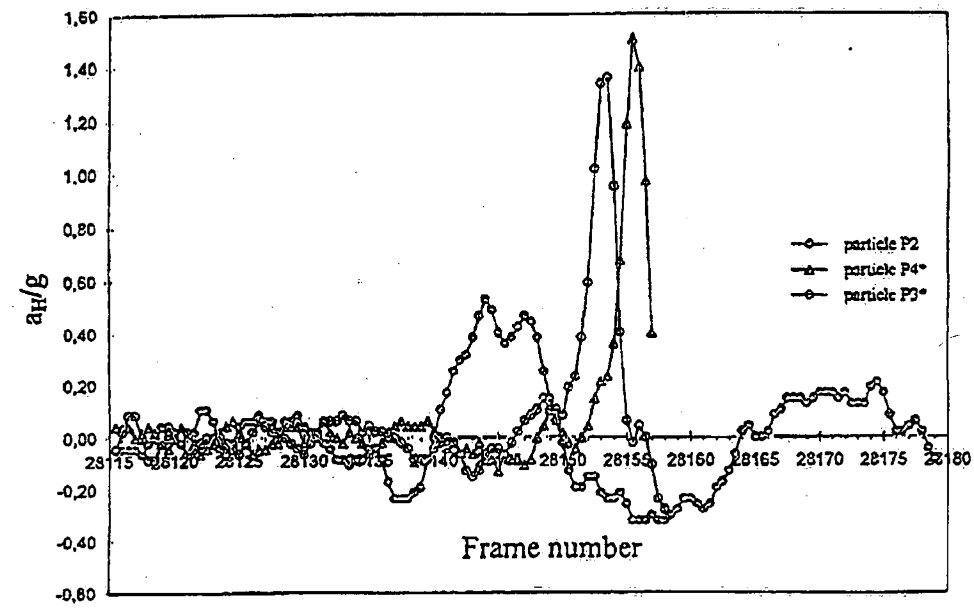

Fig. 6. Horizontal acceleration of floating particles. Experiment A15.

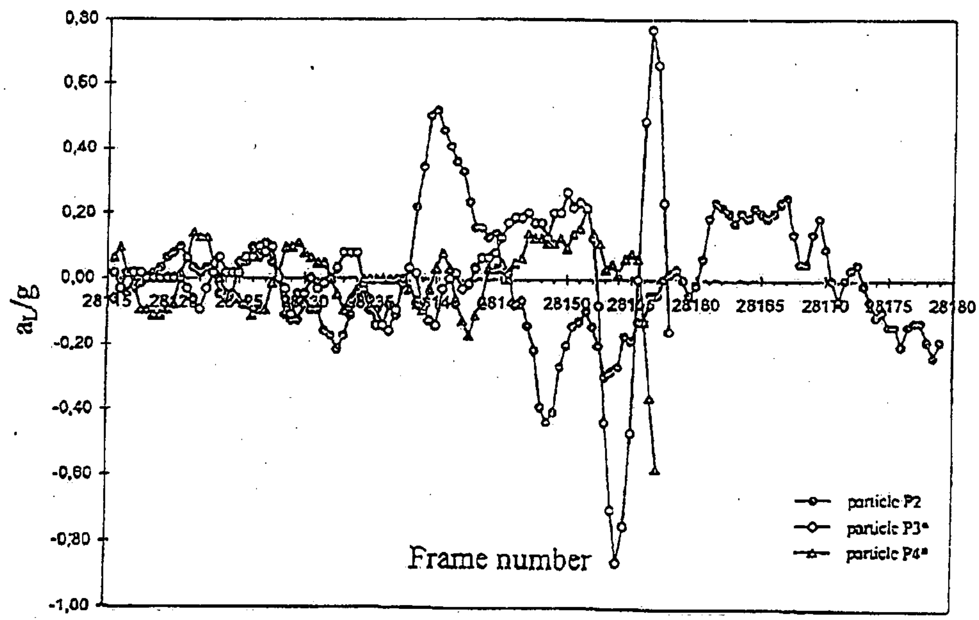

Fig. 7. Vertical acceleration of floating particles. Experiment A15.

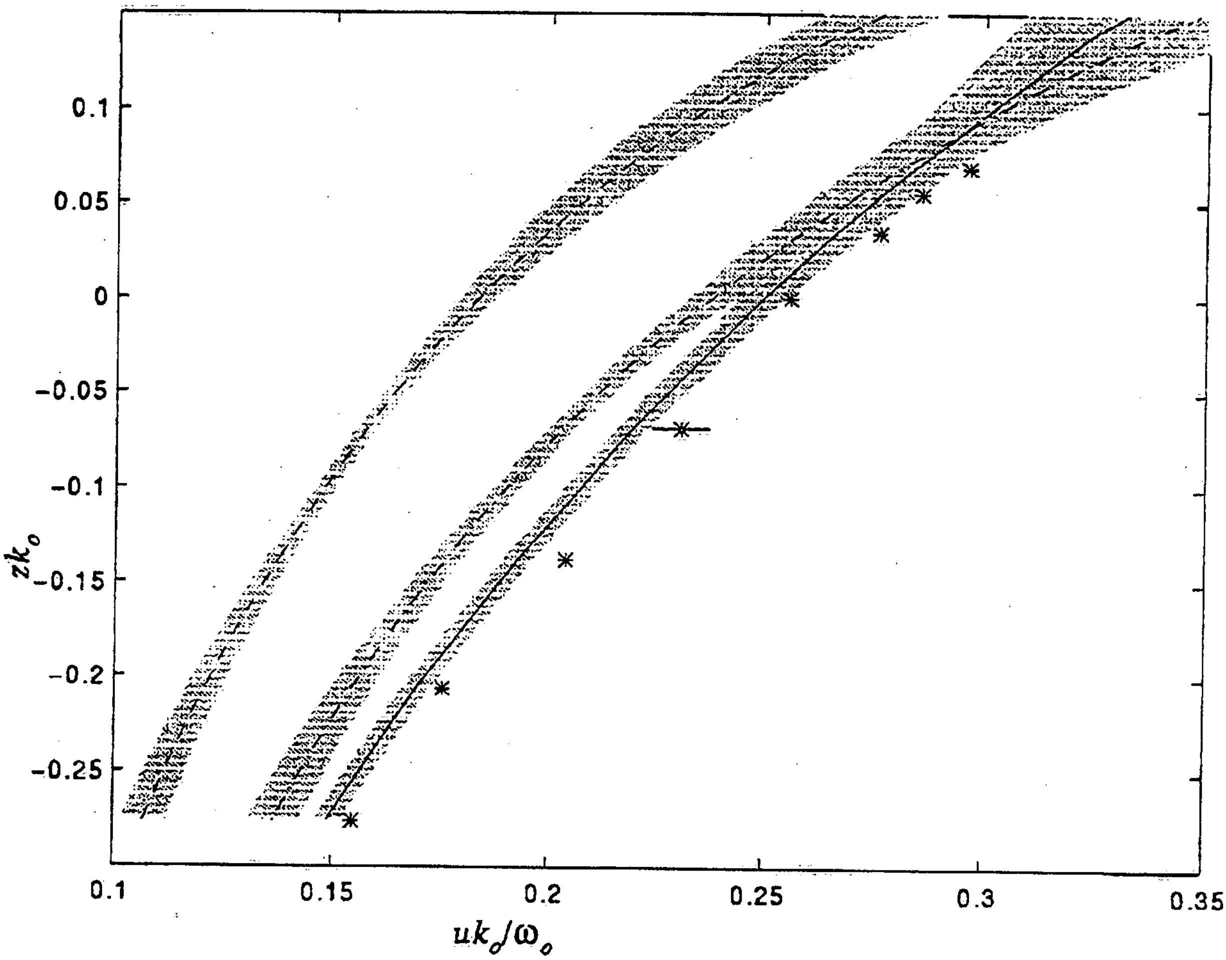

Fig. 8. Maximum horizontal orbital velocities (u) beneath the upwave of breaking, normalized by k_0 and ω_0, versus elevation (z) normalized by k_0.
*** : measured values; - - - : mean of linear superposition model; -.- : mean of modified stretching model; ___ : present model. The horizontal bar on the data point at the elevation of 0.05 represents two standard deviations about the mean. The shaded areas around the model lines enclose twice the standard deviations.**

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