Some Geometric and Kinematics Properties of Breaking Waves

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Abstract. ???

1 Introduction

Among others, the knowledge of the geometric and kinematics properties of rogue waves is important from several practical points of view. It is in particular important with regard to the safety of ships and offshore structures.

The experimental study of this phenomenon is difficult for various reasons: the phenomenon is unsteady, it occurs suddenly and intermittently, and it can display three-dimensional aspects. In-situ experiments are specially difficult because the adverse conditions and the variability of the meteorological conditions.

For these reasons, experiments in laboratory in controlled conditions appear very useful.

The geometry and the kinematics of rogue waves occurring in ocean are practically unknown and the present paper tries to bring a beginning of answer in this scope by reporting on measurements in laboratory on deep-water breaking waves which can be considered themselves as extreme waves. In addition, the experimental means used for these measurements could be easily applicable helpfulness to the study of rogue waves.

In the present report, only plunging waves are considered because their particular dangerous aspect.

2 Experimental Method and Instrumentation

2.1 The Facility

Experiments were performed in the Air-Sea Interaction Simulation Facility of IRPHE. This facility is composed of two parts: a wave-tank 40m long, 1m deep and 2.6m wide, and a closed aerodynamic circuit 60m long, 1.5m high and 3.2m wide.

Waves can be generated either by wind (wind waves), blowing up to 14m/s, or by a complete immersed wave-maker (mechanical waves), working in the range 0.5 yo
2Hz. Adverse or following water-current up to 15cm/s in deep water condition can be generated by means of pumps.

2.2 The Visualization Technique

Because breaking process is an unstationary phenomenon, visualization appears to be a privileged way for investigation. That is the reason why a visualization technique was developed whose goal is the visualization of the wave profile.

The principle of the technique is quite simple: a vertical thin sheet of light illuminates the water surface previously tinted by means of ink, so the intersection between the water surface and the light sheet makes the wave profile visible. A video-camera perpendicular to the sheet of light takes pictures of the evolution of the wave profile. The camera as the sheet of light are put on a moving carriage allowing observations and pictures at different fetches (Fig. 1).

2.3 The Image Analysis Process

The video camera takes time series of pictures which are then stored in a laser videodisc recorder. Selected pictures are then focused on an electrictonic tablet, in stop frame mode, where they are transformed into digital form for further quantitative measurements. At the present time an operator follows the wave profile by means of an electronic stylus interactive with a computer. The digitalized pictures are finally stored in the memory of the computer.

An automatic method of digitalization is now in progress to allow “statistic” measurements. Fig. 2 shows a sample of plunging wave.

3 Application to Measurements on Plunging Waves

3.1 Geometric Properties

It is well known that breaking waves, especially plunging ones, display an asymmetric shape as they approach the breaking stage, consequently, two parameters are no more sufficient to describe accurately the wave profile as it is the case for sinusoidal waves (wavelength and wave height for example).

Among the most interesting parameters, four are of particular interest, they are (see Fig. 3):
- the horizontal asymmetry factor as \( \mu : \mu = \frac{\eta'}{H} \), where \( \eta' \) is the crest amplitude and \( H \) the full wave height. This parameter describes the asymmetry of the wave with respect to a horizontal axis, the still water level, taken as a reference.
- the slope of the front part of the crest, indicated as \( \varepsilon : \varepsilon = \frac{\eta'}{F_1} \)
- the slope of the rear part of the crest, indicated as \( \delta : \delta = \frac{\eta'}{F_2} \)
- the vertical asymmetry factor, indicated as \( \lambda \); \( \lambda = F_2 / F_1 \); This parameter describes the asymmetry of the crest with respect to a vertical axis through this latter.

**Evolution of the Geometry during the Breaking.** The asymmetry increases as the wave approaches the breaking stage as indicated on Figs. 4 and 5 which display respectively the evolution of the horizontal asymmetry factor \( (\mu) \), and the one of the slope of the front part of the crest \( (\varepsilon) \).

The horizontal asymmetry increases from an initial value near of 0.5, corresponding to a symmetric wave, to about 0.9.

The slope of the front part of the crest increases, as expected, and reaches a maximum value at the breaking onset. It will be noticed that for a limiting second order Stokes wave, \( \varepsilon \) equals 0.282, which is significantly less than the present measured value 0.5.

The present results are in good agreement with the ones by [2].

The potential energy increases during the breaking, as expected, but reaches a maximum value not at the breaking onset as expected, but before this latter as shown on Fig. 6.

**Geometry at the Breaking Onset.** The asymmetry was measured at the breaking onset (see Table 1). It will be noticed the significant asymmetry with comparison to the case of a symmetric wave, and the relative good agreement, except perhaps for \( \lambda \), between the results from different origins.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( \mu )</th>
<th>( \lambda )</th>
<th>( \varepsilon )</th>
<th>( \delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computation ((ak=0.25), [3])</td>
<td>0.77</td>
<td>1.83</td>
<td>0.59</td>
<td>0.32</td>
</tr>
<tr>
<td>Experiments ((ak=0.28), [1])</td>
<td>0.76</td>
<td>1.87</td>
<td>0.54</td>
<td>0.30</td>
</tr>
<tr>
<td>Experiments ((ak=0.24), [4])</td>
<td>0.76</td>
<td>1.43</td>
<td>0.50</td>
<td>0.35</td>
</tr>
<tr>
<td>Theory: symmetric wave ((ak=0.442))</td>
<td>0.50</td>
<td>1.00</td>
<td>0.28</td>
<td>0.28</td>
</tr>
</tbody>
</table>

**Table 1. Asymmetry properties of a plunging breaker at the breaking onset, [2]**

| Fully spilling | 0.69 | 0.39 | 0.33 | 1.20 | 0.97 | 0.99 |
| Spilling | 0.75 | 0.41 | 0.31 | 1.37 | 0.93 | 1.01 |
| Plunging | 0.76 | 0.47 | 0.30 | 1.60 | 0.88 | 1.01 |
| Fully plunging | 0.77 | 0.62 | 0.28 | 2.13 | 0.80 | 1.02 |
| Symmetric wave \((2^{nd} \text{order Stokes limiting wave})\) | 0.50 | 0.28 | 0.28 | 1.00 | 1.00 | 1.00 |

**Table 2. Relation between Asymmetry and Breaker Type**
It is of current observation that the asymmetry depends on the type of breaking; it is more marked for a plunging than for a spilling.

This difference was measured: four families of breaker were distinguished, from the fully spilling, or typical spilling, to the fully plunging, or typical plunging.

Table 2 summarizes the results obtained.

### 3.2 Kinematics Properties

Five regions of particular interest were investigated, they are: the forward (or front) zero-crossing point, the rear zero-crossing point, the face of the falling water jet, the back of the overturning region and the crest of the wave.

The zero-crossing points are the points where the crest profile crosses the still water level taken as a reference: the forward (or front) crossing point is the upward zero-crossing ahead of the breaking crest, the rear crossing point is the downward zero-crossing after the crest. Fig. 7 shows that the breaking event concerns only a region located in the vicinity of the wave crest.

As about the face of the falling water and the back of the overturning region, their celerity is also constant as displayed on Fig. 8. The “breaking onset” corresponds to the time when the face of the crest becomes vertical, the plunge point, or touch-down point, corresponds to the time when the tip of the falling water jet hits the calm water surface ahead the breaking crest. Here again it will be noticed that the breaking event does not affect the forward displacement of the back of the overturning region.

The face of the falling water jet moves forward with a constant celerity equal to the one of the crest before the breaking onset, as shown in Fig. 9. The crest celerity is constant in first approximation before the breaking onset, then it decreases lightly.

The real (Langrangian) acceleration was measured on the surface of a plunging crest, and in the overturning region. Small floating tracers (respectively 15mm and 4mm in diameter), were used for these measurements.

Acceleration up to 1.5g were measured when the plunging crest meets the floating tracer (see Fig. 10); maximum acceleration of the order of 2.2g was measured in the overturning region (see Fig. 11).

These results are in relative good agreement with the numerical predictions by Vinje and Brevig (1980) (NOT in REFERENCES???, see Table 3.

Here the numerical value 1.6g, resulting from the numerical simulation, takes into account the size of the tracer (15mm).

It will be noticed that because their finite size, the tracers cannot be strictly assimilated to fluid particles, and consequently the present measurements are certainly lightly under valued.

### 3.3 Action of an Adverse Current

The action of an adverse current forms the subject of a cooperative work with the Japanese Ship Research Institute. Preliminary experiments were performed in the framework of this cooperation and some preliminary results are now presented.
Experiments were performed both on a uniform weak current ($U/C = -0.10$), and on a shear current ($U_s/C = -0.27$), where $U_s$ is the current velocity at the water surface.

**Action on the Geometric Properties.** The present results concern measurements made at the breaking onset. Table 3 summarizes the results obtained and compares them to previous results obtained by [2].

**Table 3.** Action of an adverse current on the horizontal asymmetry factor and on the crest front steepness

<table>
<thead>
<tr>
<th></th>
<th>Still water</th>
<th>Uniform current</th>
<th>Shear current</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kjeldsen and Myrhaug (1980)</strong></td>
<td>0.70</td>
<td>-</td>
<td>0.70</td>
</tr>
<tr>
<td><strong>Bonmarin (1999)</strong></td>
<td>0.54</td>
<td>0.54</td>
<td>0.49</td>
</tr>
</tbody>
</table>

It will be noticed that, at least at the breaking onset, the wave asymmetry is not significantly affected by the current. On the contrary, [2] have observed an amplification of about 13% of the crest front steepness, and of about 6% of the horizontal asymmetry factor, on a weak adverse shear current, 2% of the phase velocity, after the occurrence of the breaking stage. It is striking that a so weak adverse shear current is able to create such drastic changes.

**Action on the Kinematics Properties.** On still water, it was previously shown that the breaking event didn’t affect the displacement of the zero-crossing points: the same observation was made on current (Fig. 12). The celerity of these points depends nevertheless on the flow conditions as shown on Table 4: it decreases from still water to shear current.

When the wave profile is not sufficiently smooth, it is difficult to locate accurately the crest, then to measure accurately the phase velocity; we suggest in this case to assimilate the phase velocity to the rear zero-crossing point, indeed, we have controlled that the phase velocity so estimated is very close to the one deduced from the displacement of the crest. In addition, the zero-crossing points can be located with precision on the pictures.

**Table 4.** Action of an adverse current on the horizontal asymmetry factor and on the crest front steepness

<table>
<thead>
<tr>
<th></th>
<th>Still water</th>
<th>Uniform current</th>
<th>Shear current</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kjeldsen and Myrhaug (1980)</strong></td>
<td>0.80</td>
<td>-</td>
<td>0.75</td>
</tr>
<tr>
<td><strong>Bonmarin (1999)</strong></td>
<td>0.76</td>
<td>0.75</td>
<td>0.76</td>
</tr>
</tbody>
</table>

As previously observed on still water, the celerity of the face of the falling water jet and the one of the back of the overturning region is constant, the celerity of the...
water jet being, as expected, higher than the one of the back of the overturning region (see Fig. 13).

**Table 4.** Action of the current on the celerity of the zero-crossing points and the phase velocity, during the plunging (celerity scaled by the theoretical velocity $\frac{g}{2\pi f}$)

<table>
<thead>
<tr>
<th>Experimental condition</th>
<th>Forward Point</th>
<th>Rear point</th>
<th>“Phase velocity” 0.5 (Forward + Rear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Still water</td>
<td>0.95</td>
<td>1.08</td>
<td>1.01</td>
</tr>
<tr>
<td>Uniform current</td>
<td>0.89</td>
<td>0.90</td>
<td>0.89</td>
</tr>
<tr>
<td>Shear current</td>
<td>0.82</td>
<td>0.82</td>
<td>0.82</td>
</tr>
</tbody>
</table>

4 Conclusions

A simple visualization technique and an associated image analysis process were developed in order to measure specially geometric and kinematics properties of breaking wave profile.

The following results are worth being mentioned:

- the wave profile becomes more nad more asymmetric as the wave approaches the breaking stage
- the degree of asymmetry depends on the breaker type: it is more marked for plunging waves than for spilling ones
- because this asymmetry, more than two parameters are needed to describe accurately the wave profile
- the potential energy concentrates into the crest at the approach of the breaking stage
- preliminary measurements on a relative weak adverse current have not displayed a significant influence neither on geometric nor on kinematics properties of breaking waves at the breaking onset.

5 Prospects

(A) an automatic image analysis process is in progress in order to increase i) the number of measurements, ii) the reliability of the results
(B) the extension of the visualized field is considered
(C) further Experiments on current are planed to confirm the preliminary results
(D) from our point of view, the application of the present means to rogue waves could be helpful
6 Figures

Fig. 1. Scheme of the Visualization Device. M: Plan Mirror; LD: Light Generator; SL: Light Sheet; V: Video Camera

Fig. 2. Plunging wave in the large IRPHE Facility

Fig. 3. Definition of Wave Parameters
Fig. 4. Evolution of the horizontal asymmetry factor as a function of time, in the near-breaking region.

Fig. 5. Evolution of the crest front steepness as a function of time, in the near-breaking region.

Fig. 6. Evolution of the potential energy in the near-breaking region.
Fig. 7. Zero-crossing points position as a function of time (C₀: crest celerity before breaking onset, 144 cm/s)

Fig. 8. Face of the water jet and back of the overturning region position as a function of time (in bracket: celerity in cm/s; C₀: phase velocity before the breaking onset)

Fig. 9. Position of the crest and of the falling water jet as a function of time
Fig. 10. Real acceleration at the surface of a plunging crest

Fig. 11. Real acceleration at the water surface, in the overturning region
Fig. 12. Action of the current on the displacement of the zero-crossing points

Fig. 13. Action of the current on the water jet displacement

Acknowledgments

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References