Experimental investigation of breaking waves generated by a fast displacement ship model

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1 Abstract

Bow and shoulder wave-breaking flow, generated by a fast displacement ship model (INSEAN model 2340) has been investigated. Both the mean and the rms values of the wave height have been obtained measuring point by point by means of a finger probe. The intensity of the breaking is highlighted by the highest values of the wave fluctuations nearby the bow wave crest. The velocity field under the free surface has been measured 0.2 LPP downstream the fore perpendicular by means of 5-hole Pitot probe. These measurements have been performed just downstream the maximum of the wave fluctuation. Very detailed database for CFD validation has been carried out for the wave height. The measured velocity field completes the database and highlights interesting flow features. Uncertainty assessment of the wave height and velocity results has been performed following the AIAA Standards S-071-1995.

2 Introduction

The wave-breaking phenomena are always present in naval hydrodynamics applications. However, they are far from being completely understood. From the physical point of view, it is crucial to understand how the breaking waves are generated, and how they modify the flow field. Furthermore, from the engineering point of view it is important to have a physical model in order to take
into account properly the effect of the wave-breaking. Nonetheless, all models need a calibration that can be performed only if experimental data are available. Presently the available models for the breaking waves simulation are not able to describe the three-dimensional case, while for the 2D case, they well reproduce the classical experimental results [2], (see e. g. [3]). Colagrossi et al. [4] recently proposed a “2D+t meshless model” in order to simulate breaking waves around a ship, obtaining results that qualitatively represent the breaking scenario.

Intensive experimental works have been carried out in order to obtain experimental data on ships breaking waves. Dong et al. provide a very complete and useful database for the case of the DTMB 4817 model, measuring mean and instantaneous cross-flow by PIV system [5].

A critical point in wave breaking experiments is the effect of the surface tension, which can determine formation of capillary waves. It is necessary to obtain experimental results not affected by surface tension. First, surface tension is a physical characteristic of the water used in the experiments and it changes in different experimental realizations. Furthermore, it is not easy to measure the surface tension in order to quantify its effect on the breaking. Presence of surfactants is not avoidable in large basins, so that the surface tension can change even during the same experiment. The influence of the capillary waves on the wave breaking process is more important the more the wavelength of the breaking waves is small [6, 7]. Thus, it is necessary to perform experiments on large-scale model flows and relatively high Froude number in order to generate long waves. As a first step to realize a bigger size experiments we decided to perform measurements of the breaking waves flow generated by a large model scale (Lpp = 5.72 m) at relatively high Froude number (Fr = 0.35).

The used model INSEAN 2340 is an identical geosym of the DTMB 5415 model that has been adopted by the International Towing Tank (ITTC) as a recommended benchmark for CFD validation for resistance and propulsion (ITTC, 1996 [10]). A previous experimental study, regarding far field wave elevation has been performed for Froude numbers Fr = 0.28 and Fr = 0.41 [1]. In the case of Fr = 0.28, the wave breaking was too gentle and affected by capillary waves formation, while at Fr = 0.41 the breaking is largely developed and appears as a big plunging, with large spray formation. The actual Froude number (Fr = 0.35) has been selected on the bases of a previous photographic study. We observed that for Froude numbers larger than Fr = 0.325, the bow wave breaks without appearance of capillary waves. On the other hand at Fr = 0.35, the bow wave breaks producing large spray, which makes the wave height measurement not practicable.

3 Model geometry and experiment design

The INSEAN model 2340 is an identical geosym of the DTMB 5415 model. 5415 has been adopted by the International Towing Tank Conference (ITTC) as a recommended benchmark for CFD validation for resistance and propulsion [10]. It was conceived as a preliminary design for a surface combatant. The model, whose lines are shown in Fig. 1, presents a transom stern and a bulbous bow of peculiar shape that allows the sonar lodging. Its length between the fore and aft perpendiculars is Lpp = 5.72 m, which corresponds to a scale of λ = 24.8. The
main geometric parameters of the model are given in Tab. 1. All tests have been performed for the bare hull conditions.

The model has been made of wood at the INSEAN workshop. In order to stimulate turbulent flow, a row of cylindrical studs of 3 mm height and 3 mm diameter have been fitted on the model 0.05 Lpp downstream the fore perpendicular, with 30 mm spacing.

The experiments have been performed at INSEAN basin n. 2, that is 220 m long, 9 m wide and 3.5 m deep.

During the tests, the model was held in fixed conditions, with trim and sinkage set to the values previously determined in unrestrained conditions [8]. The nominal speed has been set to \( U_0 = 2.621 \, \text{m/s} \), corresponding to Froude number \( Fr = 0.35 \) and Reynolds number \( Re = 1.5 \times 10^7 \).

The wave height has been measured by a servo-mechanic probe (Kenek SH), mounted on a system of slides fixed to the carriage. The wave field has been obtained measuring point by point along 81 transverse cuts from the bow to about midship. The transverse displacements (2 cm) were actuated automatically, while the longitudinal ones (4 cm) were obtained manually. The acquisition time interval has been set to 2.2 s and the sample rate to 1000 Hz. The carriage acceleration has been lowered as much as possible in order to reduce the wave fluctuations due to the transient wave components (see for example [2]).

Velocity field has been measured on the port side of the cross section located 0.2 Lpp downstream the fore perpendicular, using a 5-hole Pitot probe. A classical Pitot tube has been used to measure the static pressure in an undisturbed flow region, far enough from the model. Five differential pressure transducers (Valydine DP15) have been connected to the five Pitot holes and to the static pressure hole of the Pitot tube [8].

The acquisition system was running automatically, guided by software implemented at INSEAN. Two orthogonal slides, actuated by two step-motors, drove the Pitot to the measuring point, starting from a reset position. The two step-motors have a resolution of 200 steps per revolution and the manoeuvring screw has a pitch of 10 mm, so that the spatial resolution of the device is 0.05 mm in vertical and transverse direction. The carriage speed signal was checked by the software before starting the acquisition and during the acquisition itself. When the signal was within a pre-defined range, the acquisition started. At the end of the acquisition, the system moved the Pitot to the next measuring point.

A regular grid with squared cells, whose side dimensions are \( \Delta x_g = \Delta y_g = 0.0025 \, \text{Lpp} \), has been drawn just below the free surface. The adopted sample rate has been \( f_s = 100 \, \text{Hz} \) and the acquisition time interval has been set to \( t_a = 4+6 \, \text{s} \), depending on the distance from the free surface, after a previous analysis performed to determine the time needed to have a steady average. The three-velocity components and the pressure coefficient, in the measuring point, have been calculated by software through the calibration maps [8], with real time preview.

In the following description of the results, the Cartesian frame of reference is considered fixed to the hull, with the origin at the intersection between the fore perpendicular and the undisturbed water plane. In particular, \( x \), \( y \) and \( z \) axes are in the direction of the uniform flow, starboard side of the hull and upward respectively, and the corresponding velocity components are \( u \) (axial), \( v \) (transverse) and \( w \) (vertical).
Fig. 1: test model INSEAN 2340

<table>
<thead>
<tr>
<th>Description</th>
<th>Ship</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale factor</td>
<td>$\lambda$</td>
<td>-</td>
</tr>
<tr>
<td>Length between perpendiculars</td>
<td>$L_{PP}$ (m)</td>
<td>142.0</td>
</tr>
<tr>
<td>Beam</td>
<td>B (m)</td>
<td>18.9</td>
</tr>
<tr>
<td>Draft</td>
<td>T (m)</td>
<td>6.16</td>
</tr>
<tr>
<td>Displacement</td>
<td>$\Delta$ (t)</td>
<td>8636.0</td>
</tr>
<tr>
<td>Displaced Volume</td>
<td>$V$ (m$^3$)</td>
<td>8425.4</td>
</tr>
<tr>
<td>Wetted surface area</td>
<td>$S_W$ (m$^2$)</td>
<td>2949.5</td>
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<table>
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<th>Hull coefficients</th>
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<td>$L_{PP}/B$</td>
<td>7.530</td>
<td>0.506</td>
</tr>
<tr>
<td>B/T</td>
<td>3.091</td>
<td>0.613</td>
</tr>
<tr>
<td>Entrance angle $\alpha$ (deg)</td>
<td>11.0</td>
<td>0.825</td>
</tr>
</tbody>
</table>

Table 1: Geometrical data for INSEAN model 2340 and full-scale ship.

4 Wave-height field

A preliminary photographic study has been carried out in order to set the Froude number. In particular, we observed that for low Froude numbers ($< 0.35$), the breaking occurs with appearance of capillary waves, due to the relatively small wavelength of the divergent waves. This occurs just for the ship model case, so that the analysis on the wave pattern results cannot be extended to the full-scale case.

On the other hand, for relatively high Froude numbers the breaking is characterized by presence of spray, which makes the wave height measurements not practicable. As a satisfactory compromise between the two exigencies, the Froude number has been set to $Fr = 0.35$. Photographs of the ship model
bow-wave are shown in figures 2 – 8, for seven different Froude numbers, from Fr = 0.28 to Fr = 0.45.

Figs 2-4: bow breaking wave generated by the INSEAN 2340 model at Froude numbers lower than Fr = 0.35; 1) Fr = 0.28, 2) Fr = 0.30, 3) Fr = 0.325.

Figs 5-7: bow breaking wave generated by the INSEAN 2340 model at Froude numbers larger than Fr = 0.35; 4) Fr = 0.375, 5) Fr = 0.41, 6) Fr = 0.45.

Fig 8: bow breaking wave generated by the INSEAN 2340 model at Froude number Fr = 0.35.

The wave height in the bow and shoulder region of the near field wave pattern has been measured. The mean value and the rms value have been carried out after frequency analysis and filtering, which allowed to reduce the error due to the presence of spurious (transient) wave components and electronic noise. Patterns of the mean and rms value of the wave elevation are shown in figures 9 and 10. The highest values of the rms indicate presence of fluctuations of the wave elevation due to wave breaking. The bow wave breaking is quite strong with the
maximum of the $r_{ms}$ value of about $1/10$ of the maximum wave height. A typical trace of the acquired signal in the breaking region is shown in figure 11. Although the shoulder wave crest is under the undisturbed water level, it manifests a gentle spilling wave breaking, as underlined by the grey strip in figure 10. The shoulder wave breaking is probably induced by the bow breaking wave. In fact, in the farer field the shoulder wave crest is positive and does not break [11].

Fig 9: wave height contours (mean value)

Fig 10: wave height contours ($r_{ms}$ value)

Fig 11: breaking and non-breaking wave height signal time traces
5 Velocity field induced by the bow breaking wave

The velocity field has been measured on a cross-section just downstream the bow wave front \((x = 0.2)\). Measurements have been obtained by 5-hole Pitot probe. The adopted procedure is the one described in [8]. The results are shown in figures 12-15 by contours of axial velocity component and cross-flow vectors, transverse velocity contours, vertical velocity contours and axial vorticity.

Fig 12: axial velocity contours and cross-flow vectors at section \(x = 0.2\); reference vector (top-right) is equal to the nominal velocity \(U_0 = 2.621\) m/s, the mean value of the wave height is shown by solid line ± the \(rms\) value (dashed lines).

Fig 13: transverse velocity contours at section \(x = 0.2\), the mean value of the wave height is shown by solid line ± the \(rms\) value (dashed lines).

Fig 14: vertical velocity contours at section \(x = 0.2\), the mean value of the wave height is shown by solid line ± the \(rms\) value (dashed lines).
Fig 15: axial vorticity contours at section $x = 0.2$, the mean value of the wave height is shown by solid line ± the $rms$ value (dashed lines).

The wake field generated by the bow breaking wave is clearly shown by the axial velocity and vorticity contours. Although the maximum of the axial vorticity is inside the wake, it is possible to recognize presence of vortical flow, quite far from the wake. This is more clearly shown in figure 16 where an offset value has been subtracted to the cross flow velocity components. According to this results, the picture in figure 17 displays presence of vortical flow (rolls), quite far from the hull close to the free surface.

Fig 16: cross-flow associated to the rolls (obtained subtracting an offset value to the transverse and vertical velocity components); reference vector (top-right) is equal to the nominal velocity $U_0 = 2.621$ m/s

Fig 17: evidence of rolls
6 Uncertainty assessment of the results

Uncertainty assessment of the results has been carried out following the AIAA Standards S-071-1995, for both wave elevation and velocity. Test measurement points and related uncertainties are reported in table 2 and table 3.

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
<th>(h)</th>
<th>(h_{rms})</th>
<th>Unc. ((h))</th>
<th>Unc. ((h_{rms}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.075</td>
<td>-0.09</td>
<td>3.00 10^{-3}</td>
<td>5.90 10^{-5}</td>
<td>1.45 10^{-4}</td>
<td>9.50 10^{-6}</td>
</tr>
<tr>
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<td>-0.09</td>
<td>3.91 10^{-3}</td>
<td>5.81 10^{-5}</td>
<td>7.33 10^{-5}</td>
<td>1.12 10^{-5}</td>
</tr>
<tr>
<td>0.125</td>
<td>-0.09</td>
<td>5.20 10^{-3}</td>
<td>7.96 10^{-5}</td>
<td>8.39 10^{-5}</td>
<td>1.40 10^{-5}</td>
</tr>
<tr>
<td>0.150</td>
<td>-0.09</td>
<td>9.07 10^{-3}</td>
<td>8.53 10^{-4}</td>
<td>1.61 10^{-4}</td>
<td>1.99 10^{-5}</td>
</tr>
</tbody>
</table>

Table 2: Uncertainty assessment results for the wave height

<table>
<thead>
<tr>
<th>(&lt;u&gt;</th>
<th>(&lt;v&gt;</th>
<th>(&lt;w&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>m/s</td>
<td>m/s</td>
<td>m/s</td>
</tr>
<tr>
<td>(&lt;...&gt;/U_0)</td>
<td>2.4551</td>
<td>-0.3258</td>
</tr>
<tr>
<td>Unc. (m/s)</td>
<td>0.9367</td>
<td>-0.1243</td>
</tr>
<tr>
<td>Unc. /U*</td>
<td>1.80 10^{-2}</td>
<td>8.99 10^{-3}</td>
</tr>
<tr>
<td>Unc. /U*</td>
<td>0.687 %</td>
<td>1.47 %</td>
</tr>
</tbody>
</table>

Table 3: Uncertainty assessment results for the velocity \((y = -0.1015, z = -0.005); U^* = U_0\) for the axial velocity component, while, for transverse and vertical components \(U^*\) corresponds to their range of variation in the measured field.

7 Concluding remarks

The obtained results constitute a useful database for CFD validation. In fact, the ship flow predictions obtained by numerical codes are still far to give good results in presence of 3D wave breaking phenomena, and many efforts are actually activated to improve the CFD codes.

Nonetheless, present results give important indication on the physics of the flow generated by ship (model) breaking waves.

Measurements on two more cross sections, respectively located at \(x = 0.15\) (just upstream the section investigated in present work) and \(x = 0.4\), have been planned in order to better understand the rolls generation at the bow breaking wave and the flow resulting from the shoulder breaking wave. Moreover, an extension of the investigated wave field has been planned along the shoulder wave crest [11].

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References


