EXPERIMENTAL INVESTIGATION INTO THE FLOW AROUND A MANOEUVRING LNG CARRIER ON SHALLOW WATER

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ABSTRACT

The objective of this research project is to supply information on the hydrodynamical flow around a manoeuvring vessel on shallow water. The flow patterns and the resulting forces and moments acting on the LNG carrier with twin gondola aft-body as a consequence of a drifting motion are studied. Hydrodynamic forces and moments acting on a ship change remarkably depending on the water depth. Accurate prediction of the hydrodynamic derivatives of vessels on shallow water and the ability to quantify the effect of form variations is needed. Information from these experiments is used to better understand the effect of water depth.

The flow observation, wave profile measurements and force measurements contribute to the comprehension of the observed phenomena and can be used to validate and accelerate the development of potential flow, Reynolds Averaged Navier Stokes (RANS) and semi-empirical simulation codes.

The experiments consist of towing a model of a 300 meter LNG carrier in the MARIN shallow water basin in water depth to draught ratios. State-of-the-art flow measurements with Particle Image Velocimetry (PIV) measurements were carried out up and down stream of the hull at several planes along the ship. Some representative flow fields are presented to demonstrate the influence of the water depth on the flow around the model. Besides the flow measurements the hydrodynamic forces and moments were measured.
1. BACKGROUND

The aim of the project is to acquire a better understanding of the complex three-dimensional flow around and the hydrodynamic forces on a LNG-carrier under manoeuvring conditions for different water depths including shallow water. The tests were performed in the shallow water basin of MARIN.

In the last years, the development of Computational Fluid Dynamics (CFD) for maritime purposes has made considerable progress. CFD is now a serious alternative for simple model tests. However, a powerful method to validate the results obtained with CFD was not available until the new non-intrusive technique of Particle Image Velocimetry (PIV) entered the maritime research market. In this project, PIV tests were performed to obtain detailed velocity fields around a manoeuvring ship. The results will be compared with the viscous flow solver Parnassos and the conclusions can be used for further development.

2. THE MARIN LNG CARRIER

For the study a modern twin-gondola LNG-carrier design is selected, the MARIN LNG-carrier, see Figure 2.1 and Table 1. The model is tested bare hull, no rudders nor bilge keels are fitted. Black paint is used on the model hull to minimize the reflections from the laser.

![Figure 2.1 Body plan of the MARIN LNG-carrier.](image)

Table 1 Main dimensions of the investigated MARIN LNG-carrier.

<table>
<thead>
<tr>
<th>DESIGNATION</th>
<th>SYMBOL</th>
<th>MAGNITUDE</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculars</td>
<td>$L_{pp}$</td>
<td>300.00</td>
<td>m</td>
</tr>
<tr>
<td>Length on the waterline</td>
<td>$L_{WW}$</td>
<td>308.40</td>
<td>m</td>
</tr>
<tr>
<td>Breadth moulded on WL</td>
<td>$B$</td>
<td>50.00</td>
<td>m</td>
</tr>
<tr>
<td>Draught moulded on FP</td>
<td>$T_F$</td>
<td>11.70</td>
<td>m</td>
</tr>
<tr>
<td>Draught moulded on AP</td>
<td>$T_A$</td>
<td>11.70</td>
<td>m</td>
</tr>
<tr>
<td>Wetted surface area bare hull</td>
<td>$S$</td>
<td>18690.27</td>
<td>m²</td>
</tr>
<tr>
<td>LCB position forward of midship</td>
<td></td>
<td>-0.777</td>
<td>% of $L_{pp}$</td>
</tr>
<tr>
<td>Block coefficient</td>
<td>$C_B$</td>
<td>0.747</td>
<td>-</td>
</tr>
<tr>
<td>Midship section coefficient</td>
<td>$C_M$</td>
<td>0.983</td>
<td>-</td>
</tr>
<tr>
<td>Prismatic coefficient</td>
<td>$C_P$</td>
<td>0.760</td>
<td>-</td>
</tr>
<tr>
<td>Length-Breadth ratio</td>
<td>$L_{pp}/B$</td>
<td>6.00</td>
<td>-</td>
</tr>
<tr>
<td>Breadth-Draught ratio</td>
<td>$B/T$</td>
<td>4.274</td>
<td>-</td>
</tr>
<tr>
<td>Length-Draught ratio</td>
<td>$L_{pp}/T$</td>
<td>25.541</td>
<td>-</td>
</tr>
</tbody>
</table>
3. EXPERIMENTAL SET-UP AND MEASUREMENT TECHNIQUE

3.1 General set-up

The flow observation and force measurements were carried out in the MARIN Shallow Water Towing tank which measures 220m x 15.8m x 1.15m in length, width and maximum depth respectively. The water depth in the basin ranges from 0.255m to 1.00m. During the model tests, the model was connected to the carriage by means of a six component measurement frame. The frame is located above station 10 (mid ship). The tests were carried out with the ship captive in all directions. The total forces and moments on the ship are obtained from the individual forces in 6 transducers. The model was fixed in heave, pitch and roll. The drift angle could be set through a turn-table.

The 3C-PIV camera probe was mounted to a rigid frame of the carriage. The central axis of the camera housing was aligned with the towing direction. In this way, the vertical laser sheet was aligned with the cross-sectional area of the basin. The measurement distance to the centre of the observation window was 0.90m. The width of the measuring plane was 0.375m, its minimum and maximum heights were 0.154m and 0.188m respectively. The thickness of the measuring area was about 0.016m.

The seeding mixture was released during the measurements about 10m upstream through a submerged horizontal rake with a series of small holes. The seeding material (120μm Rilsan particles) and special injection rake proved to give very satisfactory results in terms of seeding concentration, homogeneity and density.

![Figure 3.1 PIV set-up on lee side of the model in shallow water condition](image)

The sample rate of the PIV recordings was set to 10Hz. The PIV images were recorded for a duration of 20s, resulting in a total of 200 images in each run. Figure 3.1 presents the set-up of the model and the PIV probe in the basin.

3.2 Three-dimensional particle image velocimetry

The flow measurement of PIV is based on the measurements of the displacement (Δx) in a target plane between two successive light pulses with time delay (Δt).
The flow is seeded with particles and the target plane is illuminated twice with a laser. The particle positions are recorded by two special digital cameras, see [1]. One PIV-image consists of two image frames belonging to the two successive laser pulses. Special image processing software analyses the movement of the particles by comparing the light intensity in subsections (interrogation areas) of the two successive frames using correlation techniques. The output is an almost instantaneous vector field as observed by the camera. A symmetrical camera set-up was used with the laser sheet in the middle and perpendicular to the probe, as shown in Figure 3.2. The measurement distance was about 0.90 m.

A three dimensional velocity field can be derived by combination of the vector field obtained with the two cameras. Therefore, this is called stereoscopic-PIV or 3C-PIV. More background information about this method can be found in relevant handbooks, for example [2], [3] and [4].

3.3 Nomenclature

For the presentation of the results, the following co-ordinate system is used: forward, to starboard and downward are positive directions. The drift angle is positive at a positive side velocity, bow to port. The non-dimensional velocities are obtained by dividing with the towing speed. The forces are made non-dimensional by the towing speed, ship length and depth.

4. TEST PROGRAM

The test program consisted of a part to measure the hydrodynamic reaction forces due to a forced motion and a part to observe the flow around a manoeuvring vessel at shallow water. These where separated at forehand due to possible interactions. For the different water depths, the Froude depth number (Fnh) was constant resulting in a towing speed different for each water depth.
4.1 Force measurements

Force measurements were performed with the PIV probe above the water surface. These tests were performed for a range of drift angles, see Table 2.

<table>
<thead>
<tr>
<th>h/L [-]</th>
<th>Fh [-]</th>
<th>β [deg]</th>
<th>Vs [m/s]</th>
<th>15</th>
<th>-10</th>
<th>-5</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.200</td>
<td>0.42</td>
<td>10.1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.051</td>
<td>0.32</td>
<td>3.9</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.42</td>
<td>5.1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.2 Flow observations

The flow observations were performed at three water depth draught ratios (h/T = 5.1, 1.7 and 1.3) with the model under two drift angles: 10° and 15° at five positions along the ship centreline square to the centre line of the basin at luff and lee side. Table 3 present the locations and number of observation windows. The observations on luff and lee are accomplished by rotating the model in a positive and negative drift angle rather than moving the camera to the other side.

<table>
<thead>
<tr>
<th>Xpos</th>
<th>y Luff</th>
<th>Lee</th>
<th>z Luff</th>
<th>Lee</th>
<th>y Luff</th>
<th>Lee</th>
<th>z Luff</th>
<th>Lee</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.50 Lpp</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>-0.35 Lpp</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>-0.20 Lpp</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>0.05 Lpp</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>0.30 Lpp</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The position of the observation planes is indicated in Figure 4.1 for the luff and lee side observations. On shallow water only 1 vertical observation window is tested.

During the flow observation tests the hull forces are measured. By comparing these with the force measurements the influence of the PIV probe on the flow can be determined.

Figure 4.1 observation planes luff and lee side.
5. FORCE MEASUREMENTS

The measured hydrodynamic reaction force and moments of the MARIN LNG-carrier due to a forced drift motion for three water depth/draught ratios are presented in Figure 5.1.

Figure 5.1 Measured hull force and moments at $F_{h} = 0.42$.

$x$: $h/T = 5.1$, $o$: $h/T = 1.7$, $+$: $h/T = 1.3$.

Observing the non-dimensional hull forces, the forces increase with decreasing water depth. The point of application moves aft with decreasing water depth. The transverse force shows a more non-linear characteristic on shallow water than on deep water.

6. FLOW OBSERVATIONS

A selection of the observed flow fields on the LNG-carrier due to a drifting motion is presented in this chapter.

6.1 Intermediate water depth

Figure 6.1 through Figure 6.4 present the observed non-dimensional axial velocity field when sailing at $h/T = 1.7$ at a drift angle of $10^\circ$. The bilge vortices can be observed on all cross sections. In the aft ship the flow becomes complex the trailing vortex from the gondola can clearly be observed.

Figure 6.1 Sailing at $\beta = 10^\circ$, $h/T = 1.70$; axial velocity field at cross section 0.05 $L_{pp}$. 
6.2 Cross sections at aft ship

Figure 6.5 through Figure 6.7 present the axial velocity fields at cross section -0.50 \( \text{L}_{pp} \) behind the gondola while sailing at a drift angle of 10° for \( h/T \) 5.1, 1.7 and 1.3. On shallow water the trailing vortex from the gondola is more separated from the hull as on deeper water due to the stronger cross-flow underneath the ship. The wake in the aft ship is more pronounced in shallow water than in deep water. The same effects have been observed on twin gondola trailing suction shopper dredgers, see [4].
Figure 6.6 Sailing at $\beta = 10^\circ$, $h/T = 1.7$; axial velocity field at cross section $-0.50 \text{ L}_{pp}$.

Figure 6.7 Sailing at $\beta = 10^\circ$, $h/T = 1.3$; axial velocity field at cross section $-0.50 \text{ L}_{pp}$.

Figure 6.8 through Figure 6.10 present the axial velocity fields at cross section $-0.50 \text{ L}_{pp}$ while sailing at a drift angle of $15^\circ$ for $h/T$ 5.1, 1.7 and 1.3. In deeper water the wake in the aft ship at the luff side is decreased compared to the $\beta = 10^\circ$ condition. At the intermediate and shallow water condition the trailing vortex from the lee gondola is more separated from the hull as in the $\beta = 10^\circ$ condition.

Figure 6.8 Sailing at $\beta = 15^\circ$, $h/T = 5.1$; axial velocity field at cross section $-0.50 \text{ L}_{pp}$.

Figure 6.9 Sailing at $\beta = 15^\circ$, $h/T = 1.7$; axial velocity field at cross section $-0.50 \text{ L}_{pp}$. 
7. ACCURACY

For a solid validation of the CFD results, a knowledge on the accuracy of the PIV system is of key importance.

7.1 Error estimation Particle Image Velocimetry

Generally speaking, the PIV measurement uncertainty depends mainly on seeding quality, image quality and post-processing parameter values. With these conditions optimized, the peak detection is the limitation of the PIV system resulting in an accuracy of ±0.011 m/s for one set of images and ±0.001 m/s for 200 sets.

Small inaccuracies in the calibration process or adjustment of the set-up will result in velocity vectors of incorrect size and location. From the reflections on the model a drift angle offset of ±1° is observed for a small set of runs.

The disturbances of the measurements due to the harsh conditions in which the system was operating are investigated. Relatively large particles of dirt on the basin bottom, small vibrations of the carriage and images with a lower concentration of particles, induce all a negligible error.

Besides the already mentioned error inducing factors, the submerged probe alongside the model can give a substantial disturbance to the observed flow. Comparison of the measured forces with and without the submerged camera probe gives insight if possible interactions occur. On deep water, the relative difference in measured forces with and without the probe is relative small, but on shallow water the probe can significantly influence the flow. In addition to the magnitude, also the time history shows a remarkable difference. Were the recorded forces for the pure drift run almost constant, the variations in the forces during the PIV measurements is in the order of 10%. These variations can be related to a transverse shift of the vortex.

Figure 7.1 presents the relation between the transverse location of the point with minimum vorticity and the measured transverse force on the model with a submerged camera probe alongside. The solid line presents the transverse force and the dashed line the transverse location of the vortex relative to the centre line of the model. A direct relation between the vortex location and the transverse force can be observed.

This unsteady response of the flow increases with decreasing water depth $h$ and is related to the presence of the PIV system.
7.2 Conclusion

The PIV system itself is very accurate and robust in determining the velocities vectors. These velocities can however be disturbed considerably due to the submerged probe alongside the model and by inaccuracies of the set-up of the relative distances between the model and the camera.

8. VISCOUS FLOW CALCULATION

To obtain already in an early stage a qualitative comparison between the measured flow fields and flow fields predicted by a viscous flow solver, preliminary calculations have been conducted with MARIN's in-house viscous flow solver Parnassos, see Hoekstra and Eça [6] and Hoekstra [7]. This solver is based on a finite-difference discretisation of the Reynolds-averaged continuity and momentum equations with fully-collocated variables and discretisation. The equations are solved with a coupled procedure, retaining the continuity equation in its original form.

As turbulence model, use is made of the one-equation turbulence model proposed by Menter [8] without wall-functions and including the Spalart correction to account for the effects of stream-wise vorticity, described in Dacles-Mariani et al. [9].

The results presented in this paper were all obtained on structured grids with H-O topology with grid clustering near to the bow and propeller planes. See Hoekstra [7] and Toxopeus [10] for more details about the computational domain, the boundary conditions and the implementation of a drift angle in the calculations.

At present, only calculations for the water depth to draught ratios of h/T = 5.1 (in the calculations infinite water depth is modelled) and h/T=1.3 with 10° drift angle have been completed. In future studies, the other shallow water condition and other drift angles will be investigated. The number of grid nodes for the present deep water calculation was 281x97x145 in longitudinal, girth-wise and wall-normal direction respectively, amounting to approximately 4 million nodes. For the shallow water case, the computational domain consisted of 14 blocks, with a total of 4.2 million nodes. For both grids, the largest non-dimensional grid spacing $y^+_2$ at the hull or bottom was below 0.45. The Reynolds number was set...
to the required condition for deep water or shallow water, i.e. 5.9 million and 3.0 million respectively. Free surface deformation was not modelled.

In Figure 8.1, an example is given of a comparison between the measured and computed wake fields for the deep water condition at $x = -0.35L_{pp}$. In Figure 8.1 and Figure 8.2, examples are given of comparisons between the measured and computed wake fields for the deep water condition at $x = -0.35L_{pp}$ and $x = -0.5L_{pp}$ respectively. Good agreement is found, although some shifts in position and magnitude of vortices can be seen. Noteworthy is the thicker boundary layer between the gondolas predicted by the viscous-flow solver. Some differences also may be introduced by the fact that during the experiments, the deep water condition still may be affected slightly by the basin walls and floor.

![Figure 8.1 Comparison between measured (top) and computed (bottom) axial velocity fields deep water, $x = -0.35L_{pp}$](image1)

![Figure 8.2 Comparison between measured (top) and computed (bottom) axial velocity fields shallow water, $x = -0.35L_{pp}$](image2)

![Figure 8.3 Comparison between measured (top) and computed (bottom) axial velocity fields shallow water, $x = -0.50L_{pp}$](image3)

Figure 8.4 presents a comparison between the measured and computed transverse forces $Y$ and yaw moments $N$. For deep water, the prediction of the transverse force is nearly perfect, but the yawing moment is strongly under-predicted. For shallow water, the opposite observation is made. Further study, including investigation of the numerical uncertainty, is required to explain these discrepancies.
Concluding, it is found that using the viscous flow calculations, clear insight into the development of the boundary layer and vortices around the hull form and in-between the gondolas is obtained.

9. CONCLUSIONS AND RECOMMENDATIONS

The flow and forces on the MARIN LNG-carrier on shallow water where measured. The flow characteristics observed by 3C-PIV measurements seem very promising for future CFD code validation. The flow measurements were not polluted by the harsh experimental conditions and the 3C-PIV system proved to be very robust and reliable. In the shallow water conditions used for the tests, down to 3 cm distance between the probe and the basin ground was encountered, which generated dust particles in the field of view and laser reflections from the free surface and the bottom. Nevertheless, an important number of valid vectors were obtained on each vector map.

This study is a indispensable contribution to the current knowledge of flow around a twin-gondola ship on shallow water.  

10. REFERENCES