Validating Force Calculations using OpenFOAM© on a Fixed Wigley Hull in Waves

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1 Introduction

The prediction of the fuel consumption of a ship on its desired route is interesting for many reasons, most important of which are the environmental impact and the cost of the fuel itself. Such a prediction can either be made based on experience, data from similar hulls on similar routes or; through *a priori* predictions based on fluid dynamic modelling and experiments. In a world where the allowed margins of error on the predictions of cost- and environmental impact grows smaller, the later is more suitable since it allows for optimisation and corrections to be made earlier in the design spiral.

Numerical predictions of the added resistance of a ship in waves have historically been made using the assumption that viscosity has no impact in such methods as Maruo (1957), Gerritsma and Beukelman (1972) and Faltinsen et al. (1980). The problem with using potential flow is that it is too mathematically complicated to arrive at a solution accounting for all phenomena involved. The solution therefore, comes with a long list of assumptions, linearisations and simplifications. In most cases when this is shown to influence the results, it can be adjusted for using empirical corrections but no method has been show to work for all types of hulls in all sea states. It is therefore hard to tell if the weakness of potential flow for the purpose of describing a ship in waves lies in the original assumptions or if it is due to the many assumptions used to make the problem mathematically approachable. Furthermore, using potential flow does not allow for detailed coupling between the flow around the hull and the performance of the propeller. These are the two main causes of decreased performance in waves and should be considered together in any prediction of said performance(Prpić-Oršić and Faltinsen, 2012).

2 Aim

A RANS based prediction allows for phenomena such as the behaviour of the boundary layer under the waves and other viscous effects to be modelled. Even though a prediction based on RANS modelling comes with much fewer assumptions, the complexity of the problem means that it is very sensitive to meshing, selected schemes, boundary conditions etc. For example; to accurately predict the forces on the hull, the correct motions are needed, this in turn requires accurate force prediction which can lead to large discrepancies if the exciting force had a small discrepancy to begin with. Incorrect predictions of the phase of the hydrodynamic forces is something that has been highlighted in previous CFD workshops as one of the weaknesses of using RANS (Larsson, 2010).

For this reason this paper concerns a fixed hull in waves. Previous studies have shown that using a fixed hull can give a good insight into the force distribution on the hull and, using a body force model for the propeller, predict the self propelled performance of a ship with good accuracy (Turnock et al., 2010). Using a fixed hull also eliminates any progressive expansion of errors due to phasing problems which allows for more detailed studies of phenomena such as boundary layer disturbances due to the waves and how this affects the propeller inflow.

To thoroughly validate the performance of OpenFOAM for predicting the forces on a fixed hull in waves, a comparative study with several wavelengths was conducted. The experimental data is provided from a study of fixed Wigley hulls in waves by Journée (1992). For further comparison, predictions made using a non-linear Boundary Element Method (BEM)are also included (Kjellberg, 2011).

3 Setup

Waves were generated and dissipated using the relaxation-based wave generation toolbox waves2Foam (Jacobsen et al., 2012). The length of the relaxation zones used in the wave generation were chosen to match the wavelength of the longest wave in the validation case (6m.) For all cases in this paper, the speed was corresponding to $Fn = 0.2$.

The geometry and boundary conditions were set up to match the conditions of the experiments. Forward speed was achieved by imposing a steady current and wind velocity in the domain and thus all boundary

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conditions on walls were set to a slip-type. The outlet was set to vary between a Neumann type boundary condition (zero gradient) for the velocity if the velocity vector points into the domain and a Dirichlet type (with a fixed value on the flux representative of the freestream) if the velocity vector points out of the domain. This was done to increase the stability of the outlet. The inlet boundary condition was set so that the volume fraction and velocity follows those of the waves being generated in the adjacent relaxation region ensuring that the all gradients over the inlet boundary equals zero.

For turbulence modelling, the $k - \omega$ SST model(Menter, 1994) was used with small initial values of k to represent some initial turbulence present in the tank.

3.1 Validation hull

The used hull was the one labelled "Wigley III" by Journée (1992), the particulars of which are shown in Table 1.

Table 1: Particulars of validation hull

L_m	=	3 m	B_m	=	0.3 m	a_2	=	0.2
T_m	=	0.1875 m	∇_m	=	0.0780 m^2			
C_{33}	=	6119	C_{55}	=	2874			

L_m, B_m and T_m are the length, width and draught of the hull. C_{33} and C_{55} are the stiffness terms in the equations of motion for heave and pitch respectively given by the geometry and ∇_m is the volume displacement of the hull. a_2 gives the shape of the hull as:

$$z_m = \frac{B}{2}\left(1 - \frac{y_m}{T_m}^2\right)\left(1 - \frac{2x_m}{L_m}^2\right)\left(1 + \frac{2a_2x_m}{L_m}^2\right) \tag{1}$$

with x_m,y_m,z_m being a hull-fixed system originating amidships, on the waterplane and on the centreline with the same orientation as in Figure 1. Above the waterline, the cross section was fixed at the one when $y_m = 0$.

3.2 Geometry

The basin has the same principal dimensions as the Delft University of Technology towing tank where the experiments were conducted. Only a section of the tank before and after the hull just enough to capture the relevant flow features and waves was used. Furthermore two relaxation zones were allowed before and after the measurement region for generating and dissipating waves.

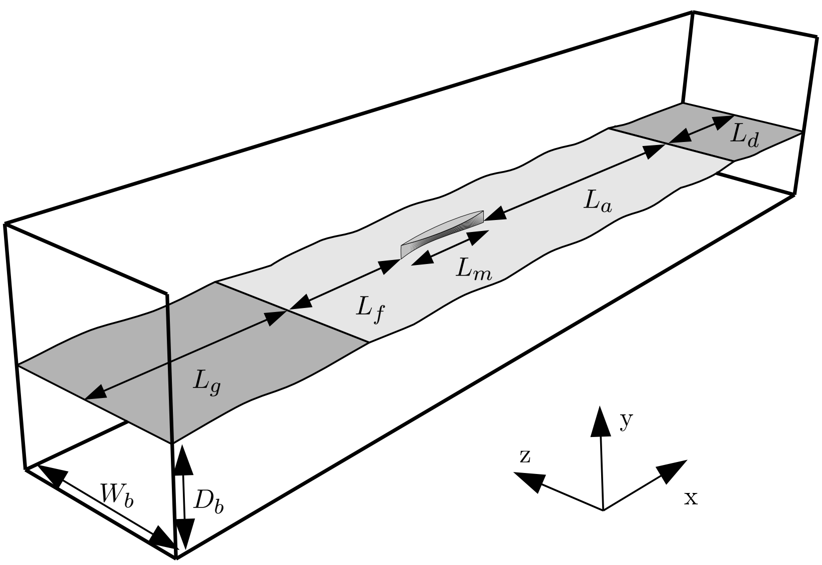

Figure 1: Geometry

Table 2: Domain particulars

D_b	=	2.5 m	W_b	=	4.22 m
L_g	=	6 m	L_d	=	6 m
L_f	=	L_m	L_a	=	$3L_m$

3.3 Meshing

When simulating a ship travelling in waves, there are several requirements of the mesh. Away from the hull, the main requirement is that it should allow for the undisturbed propagation of incoming and ship-generated waves. Close to the hull and in the wake, the mesh should be as uniform (aspect ratio 1) as possible to more accurately capture detailed flow features.

The impact of the mesh density in the free surface region on the quality of the propagating regular waves was investigated prior to generating the final mesh. As a measure of quality, the reduction in the height of the wave at a point four hull-lengths downstream of its generation was used. This was done for varying numbers of cells in the horizontal and vertical directions and for varying wavelengths. The amplitude was kept constant at $\zeta = 0.023m$ which is close to all the amplitudes in the validation case.

Because the impact typically varies with wave elevation and -steepness, there will be an optimal mesh for each wave in the testcase. However, in the interest of simplicity, one mesh was used here for all cases. Because of this, the lowest performance across the range of wavelengths was chosen as representative. This is shown in Figure 2.

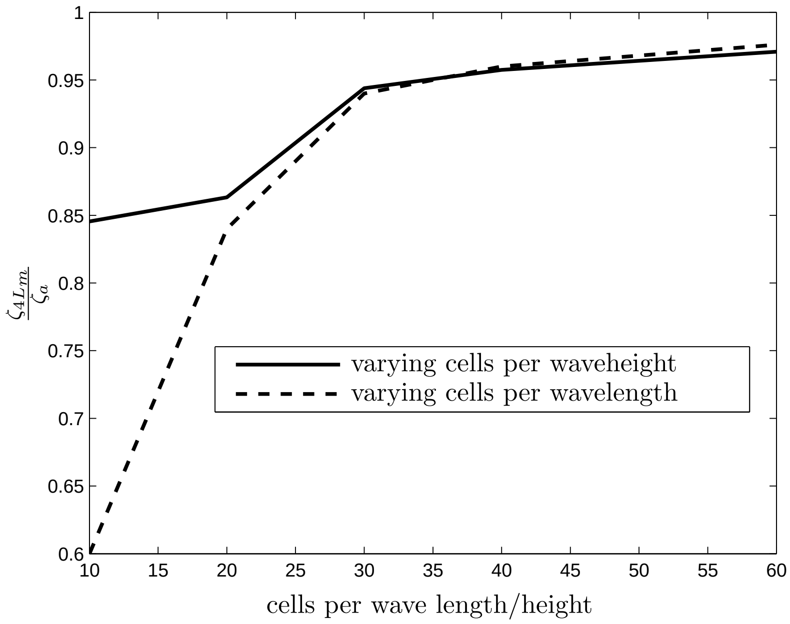

Figure 2: Results of mesh independence study for wave propagation

From Figure 2, it can be concluded that 30 cells per waveheight and 30 cells per wavelength should be enough to ensure undisturbed propagation. Because one mesh is used for all cases, the spacing is based on the shortest wavelength in the series. Because the wavelength is much greater than the waveheight in this case, this means that relatively high aspect ratio cells are needed in the free surface region. Since this is not desirable close to the hull, a way of blending the mesh refinement between these two different regions is needed.

This is achieved by selecting and refining cells based on distance from the body and the region of the free surface. The procedure is illustrated in Figure 3 and can be described as follows:

(a). If more body refinement is needed, select cells with a distance d_b from the body. If more vertical free surface refinement is needed select cells where $|y| < \zeta$.

$\rightarrow$ Refine vertically

(b). If more body refinement is needed, Select cells with a distance d_b from the body. If more horizontal free surface refinement is needed select cells where $|y| < \zeta$.

$\rightarrow$ Refine horizontally

(c). Shrink the distance d_b and repeat step (a)

(d). Repeat step (b)

(e). When all refinement levels have been reached, snap to body and grow boundary layer mesh.

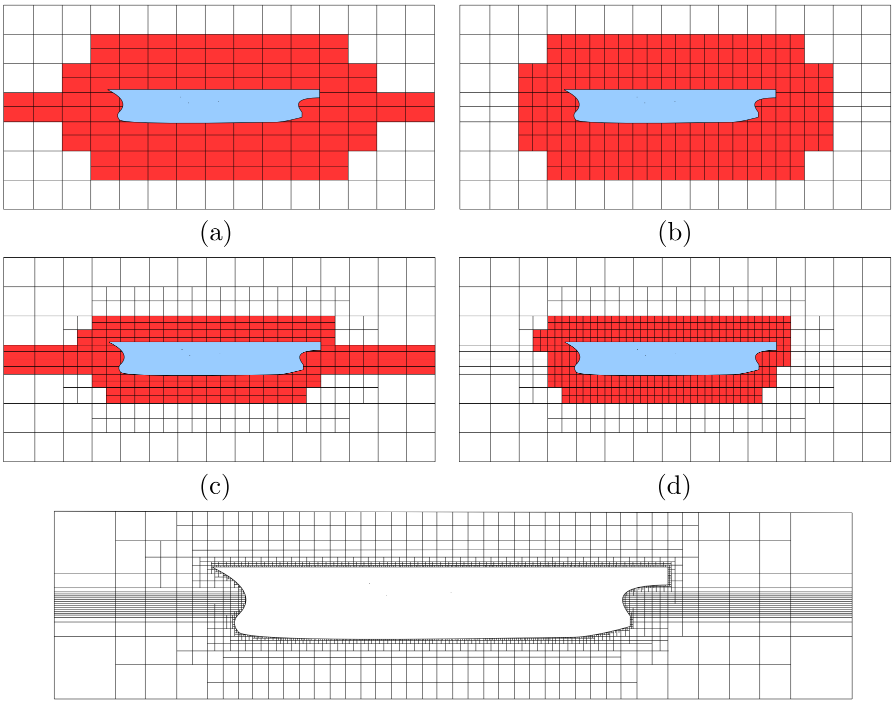

Figure 3: Mesh generation strategy

Steps (a)-(d) are achieved using the native OpenFOAM-tools for cell selection and splitting (cellSet and refineMesh) using an automated script while snapping to the surface and boundary layer mesh generation are done using the standard meshing tool snappyHexMesh. The boundary layer mesh was added to achieve a y^+-value of 50-60 for the hull. The final mesh contains 7M cells.

3.4 Solving and data recording

The used solver was the standard OpenFOAM VOF solver interFoam with modifications applied to incorporate the relaxation zones. Wave elevations were measured by probing the volume fraction α across the free surface region. Two adjacent points (i and $i-1$): one where $\alpha < 0.5$ and one where $\alpha > 0.5$ were found and the point where $\alpha = 0.5$ calculated as

$$\zeta = y_{i-1} + \frac{\alpha_{i-1} - 0.5}{\alpha_{i-1} - \alpha_i} (y_i - y_{i-1}) \tag{2}$$

from which the amplitude ζ_a could be extracted by averaging over several wave periods. The forces on the hull were calculated using the OpenFOAM force library which is based on wall shear stress and pressure distribution. These were calculated for each face and summed over the hull to give total forces and moments.

4 Results

The results of the validation study are presented as amplitudes of the surge force F_{xa}, heave force F_{ya} and pitch moment M_{za} and their phases $\varepsilon_{1,3,5}$ relative to the wave elevation amidships.

The amplitudes are nondimensionalised as

$$F''_{xa} = \frac{F_{xa}}{k\zeta_a \rho g \nabla_m} \tag{3}$$

$$F''_{ya} = \frac{F_{ya}}{\zeta_a C_{33}} \tag{4}$$

$$M''_{za} = \frac{M_{za}}{k\zeta_a C_{55}} \tag{5}$$

where k and ζ_a are the wave number and -amplitude of the incident waves.

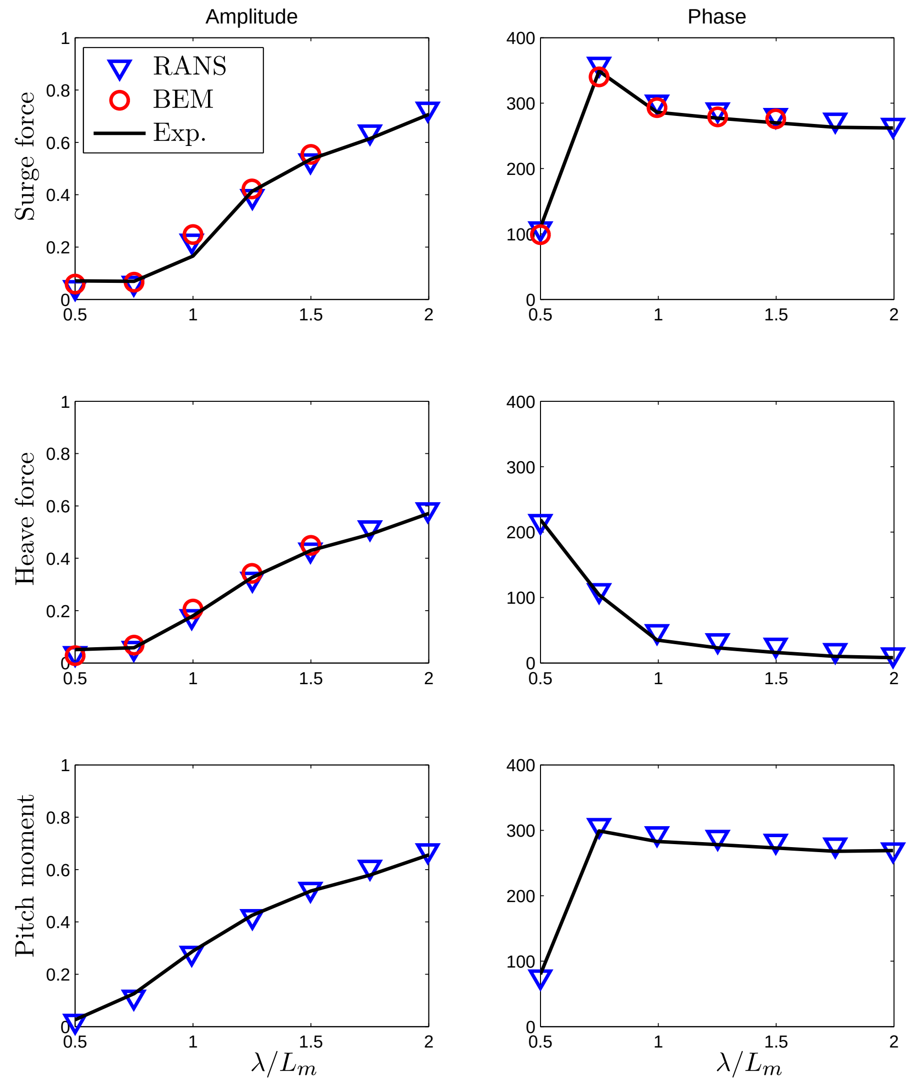

Figure 4: Results of validation case

5 Conclusions

Both the RANS and the BEM show good correlation with experimental results in terms of amplitude with RANS having the best performance. The RANS prediction of the phases is slightly worse than that from the BEM with a discrepancy of around 10^o across the range of wavelengths. This shows that, for a fixed hull, the viscous contribution to the amplitude of the force variation is minimal. There is however an effect on the mean values of force when viscosity is considered. This is shown in Figure 5. This does not say much about the actual viscous effect on a moving hull since motions would greatly increase the pressure contribution as well as move the hull to other positions relative to the waves. It is however interesting when considering self propulsion since a change in the viscous force means a disturbance of the boundary layer which means an altered inflow to the propeller. This has implications for bow design since the flow at the bow has been shown to be very influential for the character of the boundary layer further aft (Landweber and Patel, 1979).

This study has shown that forces on a fixed hull can be accurately predicted using the described setup. The next step in this study will be to use this setup to investigate what changes in the shape (especially above the waterline) at the bow does to the viscous force distribution on the hull.

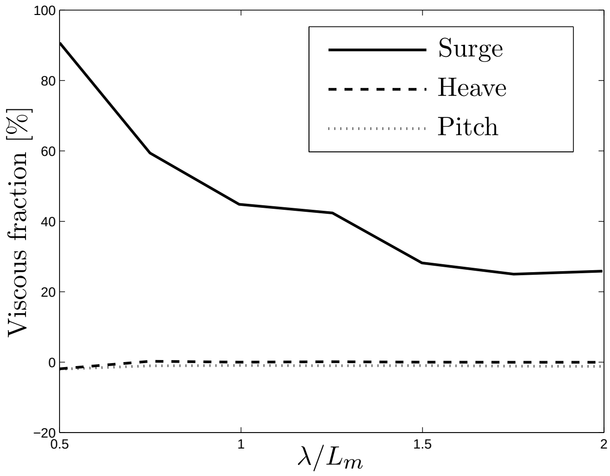

Figure 5: Viscous contribution to the increase in mean values of force/moment

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