Self propulsion modelling of the KCS container ship using an open source framework

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1 Introduction

Recent Numerical Towing Tank Symposia have shown a wide variety of applications of CFD to problems relating to ship performance. More often than not, these depart from the traditional calm water resistance calculation. One reason for this could be the relative confidence established in the ability of Navier-Stokes (NS)-based methods to predict the multiphase flow around a hull in calm water as shown in recent CFD workshops (Larsson et al., 2014). Years of experience with such simulations have also given confidence in supporting methods such as mesh generation etc. More confidence means that the methods are more likely to be used to a larger extent in the ship design process. When looking to build on this confidence to create more comprehensive models, one option is to consider ship resistance and propulsion in a more holistic way.

Experimental measurements on self propelled models is a common method to estimate the powering performance of a ship (Molland et al., 2011, p 151-152). These can be replicated by including the rotating propeller geometry in the NS solution (Carrica et al., 2010; Lübke, 2005). However, in doing so a significant amount of extra computational effort is needed compared to the bare hull case. Using for example an Arbitrary Mesh Interface (AMI) to achieve propeller rotation also complicates the mesh generation process. In order to maintain the attractiveness of NS based methods for use in the ship design process when moving to more holistic simulations, these problems should be addressed.

A NS based solver coupled to a simplified propeller model is a way of simulating self propelled ships without a significant increase in the computational cost (Fu et al., 2010; Phillips et al., 2008; Simonssen and Stern, 2005; Turnock et al., 2010; Windén et al., 2014*a*). Such coupled solvers are usually achieved through body force modelling where the momentum induced into the fluid by the propeller is represented by an extra source term in the momentum equation. However, formulating such a coupling may still require special treatment of the mesh in the stern area to suit the formulation of the chosen propeller model. Furthermore, if considering manoeuvring simulations or simulations in waves, identifying the strength of the body force and the influence of the surrounding velocity field on a propeller behind a moving hull is a challenging task.

Determining how applicable self propelled simulations using body force models are for predicting ship performance is important to establish more experience around the more holistic approach to marine CFD. A framework for coupling a NS based solver with an arbitrary body force model on an arbitrary (dynamic) mesh has been suggested by Windén et al. (2014*b*). This framework would allow the body force approach to be evaluated for simulations of self propelled ships in calm water, manoeuvring, and wave problems. Furthermore, it supports run-time estimation of the nominal wake. The framework allows for propeller models as well as RPM control schemes to be developed by the user using simple templates only requiring the model-specific equations as input. The framework is implemented in the open source CFD toolbox OpenFOAM (OpenCFD and The OpenFOAM Foundation, 2010) and so is available to the CFD community.

In this paper, the framework is used to evaluate the applicability of an Unsteady Reynolds Averaged Navier-Stokes (URANS) flow solver coupled with a Blade Element Momentum theory (BEMt) propeller model to study self propulsion in calm water and in waves. This paper is meant as an example of how the framework can be used. More detailed information on the specific implementations is given by Windén (2014*a*) and a detailed description of the framework itself is given by Windén et al. (2014*b*).

2 The numerical towing tank

The flow is modelled using the URANS equations, Eqn. 1

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = \frac{1}{\rho}\left(\mu \frac{\partial^2 \overline{u}_i}{\partial x_j^2} - \frac{\partial \tau_{ij}}{\partial x_i} + \frac{\partial \overline{p}}{\partial x_i} + F_v\right) \tag{1}$$

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Table 1: Particulars of the KCS model hull.

Scale			1:52.667		
Length Lpp	=	4.3671 m	Beam B	=	0.6114 m
Draught T_m	=	0.2051 m	Displacement ∇	=	0.3562 m^3
Prop. radius R	=	0.0750 m	Hub radius r_H	=	0.0126
Centre of gravity	=	(-0.0647 -0.0668 0) m	Prop. position	=	(2.139 -0.1273 0) m

Table 2: KCS meshes.

	Mesh size	BEMt mesh size	Cells in disk	Time spent on framework
Fine	17.7M	10x10x1	3500	2.4%
Medium	10.8M	10x10x1	2600	1.6%
Coarse	3.1M	10x10x1	400	1%

where F_v is the body force. The free surface is captured using the VOF method and waves are generated using the wave generation toolbox waves2Foam for OpenFOAM. (Jacobsen et al., 2012). The $k-\omega$ SST model (Menter et al., 2003) is used for turbulence closure.

A simplified version of this simulation with a free to surge hull at very low speed was conducted by Windén et al. (2013). In this model, the nominal wake was probed directly at half a diameter forward of the propeller plane. This approach neglects the effects of the propeller induced velocities at this location. The improved model probes the effective wake at the propeller plane and corrects for the propeller induced velocities using the inflow factors known from the BEMt solution as well as a custom correction as suggested by Windén (2014*a*).

The simulation is compared to experimental results available for the self propelled KCS container ship. The particulars of the hull are given in Table 1. The coordinate system Oxyz is right handed with x being the surge, y the sway and z the heave direction respectively.

Three different meshes are created to estimate the grid influence on the results in the following sections. An overview of these are given in Table 2. Here, the size of the Finite Volume (FV) mesh is given as well as the number of radial, circumferential and axial sectors used in the BEMt calculations. Furthermore, the number of FV cells within the propeller disk (0.2 diameters thick) which are given an active body force is also given. Finally, Table 2 presents the overall computational time spent on the framework (including propeller modelling, mapping between FV and BEMt meshes and any other activities relating to the coupling) as a percentage of the total computational time.

Comparison with experimental data is made in terms of the total resistance coefficient C_t as well as the coefficients of thrust K_T and torque K_Q. These are defined as

$$C_t = \frac{F_x}{0.5\rho U^2 S_0} \tag{2}$$

$$K_T = \frac{T}{\rho n^2 (2R)^4} \tag{3}$$

$$K_Q = \frac{Q}{\rho n^2 (2R)^5} \tag{4}$$

where F_x is the surge force, T is the thrust and Q is the torque. n is the rotation frequency of the propeller and S_0 is the wetted surface area which is taken as $S_0 = 0.1803Lpp^2$. The presented discrepancies in these coefficients are relating to the relative error between the calculated value and the experimental value.

3 Input data to the framework

Apart from the set up of the flow solver which is the same as it would be for a standard bare hull resistance calculation, the following extra input parameters have been used to conduct the simulation. All of these are provided in two text files (C++ dictionaries) which are read by the framework. The parameters relating to the propeller are given in one dictionary named *propellerDict* which contains

- the name of the propeller model to be used. In this case BEMt. Other options are made selectable when a user creates a new model using the template provided with the framework.

- the name of the RPM control scheme to be used. A set of basic controllers are available, more options are made selectable when a user creates a new model using the template provided with the framework.
- limiters for the controller, e.g. max. permitted RPM increase rate and max. permitted RPM.
- U,g,ρ and other constants.
- the propeller position and orientation in initial state.
- For the BEMt: propeller radius, hub radius, pitch and chord distribution, blade area ratio, number of blades and the number of discretisation steps in the radial and circumferential directions and order of interpolation scheme to map between BEMt and FV meshes.

The parameters relating to the hull are given in another dictionary named *hullDict* which contains

- the centre of rotation, mass, moment of inertia and other parameters relating to the hull.
- the name of boundary patch in the FV mesh which represents the hull.
- definitions of surge and heave directions (the rest are found automatically.)
- for each degree of freedom, definition if this is free, locked or forced (PMM.)

4 Results for the KCS at $Fn = 0.201$ at 840 RPM

Experimental results for the KCS at a fixed RPM of 840 and at $Fn = 0.201$ are available as part of the SIMMAN 2014 workshop on ship manoeuvring (FORCE, 2013). In these simulations, the hull is fixed in heave and pitch in accordance with the experimental set up. The correlation between the experimental results and simulations on the three different meshes are shown in Table 3.

Table 3: Propulsion properties (at 840 RPM) for KCS at $Fn = 0.201$ compared to experimental data.

		EFD	Coarse	Medium	Fine
$1000C_t$	recorded	5.318	5.0898	5.154	5.563
	error	-	-4.296%	-3.083 %	4.608%
K_T	recorded	0.302	0.262	0.2808	0.281
	error	-	-13.245%	-7.020%	-6.954%
K_Q	recorded	0.0429	0.0425	0.460	0.0461
	error	-	-0.932%	7.226 %	7.459%

In these simulations, the dummy propeller controller *fixedRPM* which is available in the framework is used to keep the RPM fixed at all times.

5 Results for the KCS at $Fn = 0.26$ at model self propulsion point

For $Fn = 0.26$, experimental data is available for evaluating the ability of the framework to find the self propulsion point in calm water (Larsson et al., 2010, Test case 2.3b). Here, the $selfPropFinder$ propeller controller is used to control the RPM in order to find the point where $F_x = T$. Contrary to the experimental set up, the model is fixed in heave and pitch in this simulation. In the experiment, a pitch of 0.143° and a sinkage of 0.00833 m was measured.

6 Results for the KCS at $Fn = 0.26$ in waves

After the self propulsion point is found at $Fn = 0.26$, the RPM is fixed and the model is subjected to regular head waves of $\lambda/L_m = 0.85$ and $\zeta_0 = 0.015$ m.

In this section, time histories of relevant quantities are presented both for the time when the hull is subjected to waves but also throughout the self propulsion point finding process. This is done to illustrate

Table 4: Propulsion properties (at model self propulsion point) for KCS at $Fn = 0.26$ compared to experimental data.

		EFD	Coarse	Medium	Fine
$1000C_t$	recorded	5.222	-	-	4.8305
	error	-	-	-	7.50%
K_T	recorded	0.2530	-	-	0.2215
	error	-	-	-	-12.45%
K_Q	recorded	0.0408	-	-	0.0381
	error	-	-	-	- 6.62%
n	recorded	14.15	-	-	14.76
	error	-	-	-	4.31%

the different capabilities of the framework in one continuous time series. Figure 1 shows the development of the surge force where the increases due to switching on the propeller and upon encountering the waves are highlighted. Figure 2 shows the development of the propeller RPM as well as the average (over propeller disk) advance ratio $J = \overline{U_n}/2nR$. Here U_n is the estimated local nominal wake. Finally, Figure 3 shows the development of the thrust and torque coefficients.

Animated images showing the force distribution on the hull and the nature of the unsteady wake for this simulation has been presented by Windén (2014*b*).

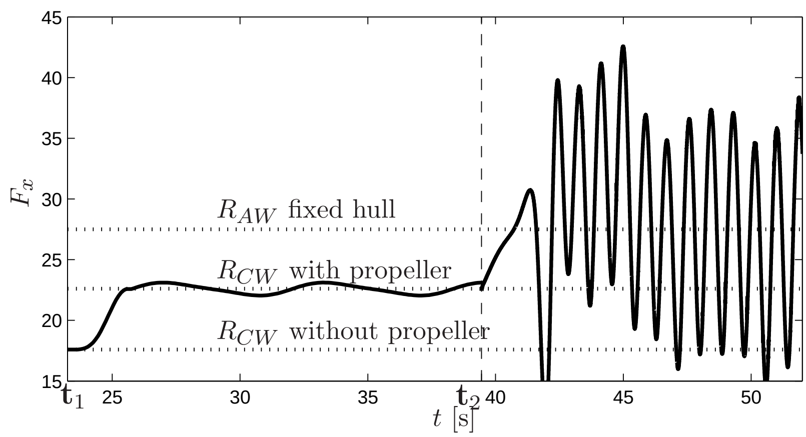

Figure 1: Development of surge force after propeller switch on ($\mathbf{t}_1$) and after wave switch on ($\mathbf{t}_2$).

7 Conclusions

The results shown here indicate how the framework presented by Windén et al. (2014*b*) can be used to study self propulsion of a container ship. A BEMt propeller model is used within the framework together with different propeller controllers. The results for $Fn = 0.26$ where the self propulsion point was found by the framework by varying the RPM show reasonable agreement with experimental data. The errors are comparable to others reported at the Gothenburg 2010 CFD workshop Larsson et al. (2010, p 240-244). They are however relatively high and are mostly comparable to the upper range of these reported values at previous workshops. The difference here is that, using the framework, this is achieved with very little extra computational effort. About 1-2% of the computational time is spent on the framework, this includes all propeller modelling, mapping between meshes, probing of the nominal wake etc. Furthermore, no further attention is paid to the mesh other than what would have been done in a standard resistance simulation. This is encouraging for the use of body force modelling as a practical tool in the ship design process. It is likely that, by spending more time on better designing the mesh and by improving the propeller model, the results could be improved. The main purpose of this study is to encourage more similar studies in order to establish further confidence in self propelled simulations.

From the simulation in waves it can be concluded that the variation of thrust and torque is of relatively low amplitude. The mean values of the oscillations in waves correspond roughly to the calm

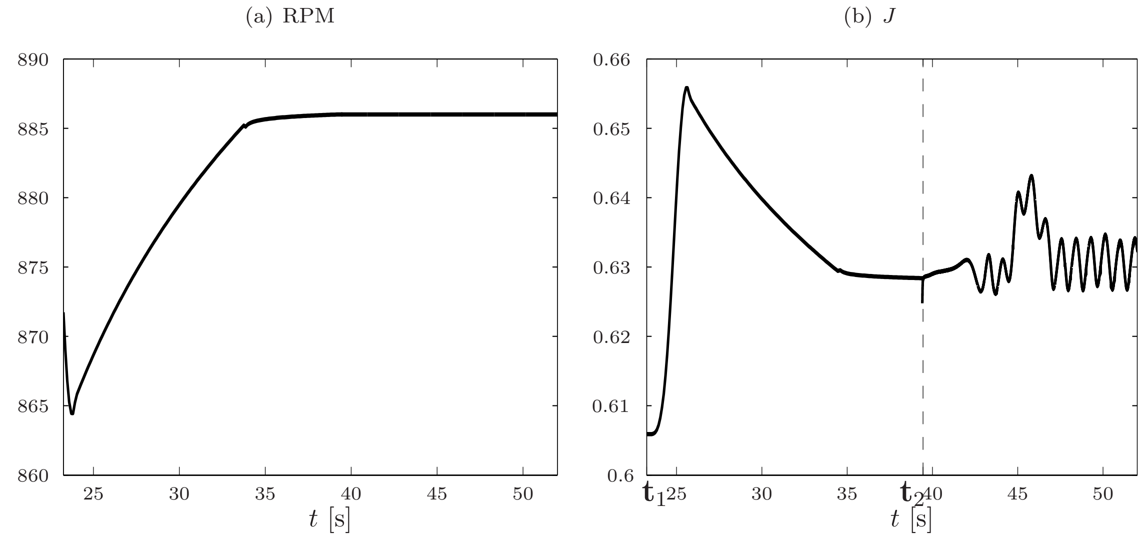

Figure 2: Development of RPM (a) and average J (b) after propeller switch on ($\mathbf{t}_1$) and after wave switch on ($\mathbf{t}_2$).

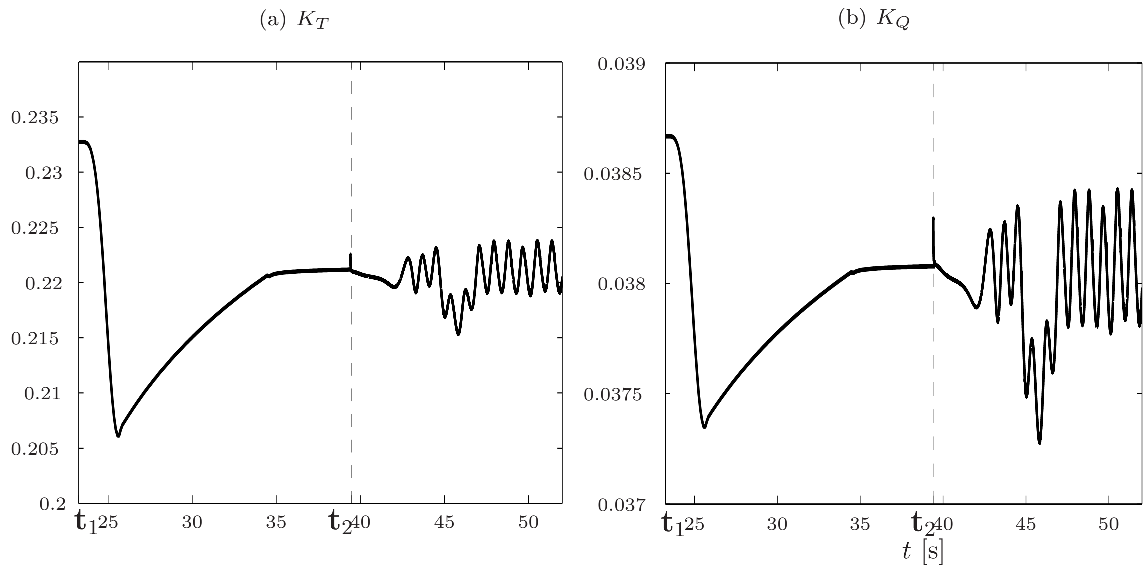

Figure 3: Development of K_T (a) and K_Q (b) after propeller switch on ($\mathbf{t}_1$) and after wave switch on ($\mathbf{t}_2$).

water equivalents. This can be related to previous experiments by Nakamura et al. (1975) suggesting that the open water coefficients remain at the same average value even under waves. This seems to hold true even in this case when the hull is present.

Acknowledgements

This work was carried out within the research project entitled *ship design for enhanced sustainability* which is sponsored by the Lloyd's Register Foundation whose support is gratefully acknowledged.

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