Self propulsion in waves using a coupled RANS-BEMt model and active RPM control

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1 Introduction

The flow over a ships stern is very complex, involving a thick boundary layer, viscous-inviscid interaction, a complex turbulent flow-field and the action of a propulsor (ITTC, 1990). Reviewing these flow features numerically is a challenging task, since it requires not only accurate prediction of resistance and wake flow, but also good prediction of the propulsor. When considering self propulsion in waves, more complexity is introduced in the form of ship motions and unsteadiness introduced by the passing waves. One simplification in the analysis of the above system without compromising the predictive accuracy is to couple a propeller performance code in an iterative manner to predict the combined flow field.

Several twoway coupling approaches have been developed by various authors with different levels of complexity for investigating ship stern flows. An example of such an approach was presented by Badoe et al. (2012), who described a coupling using a body force model and a load distribution based on the Hough and Ordway (1964) circulation to determine the propeller forces.

Other possibilities involving coupling of a potential flow code to a RANS code has been described by Laurens and Cordier (2003) using the velocity field calculated in the near-field downstream flow from the propeller, simulated by the resolution of the potential problem as inlet boundary conditions within the RANS calculation. Each of these approaches have advantages in terms of accuracy, computational efficiency and level of detail.

The present paper aims to present a methodology for coupling a RANS code and a Blade Element Momentum theory (BEMt) model for the propeller. This is done as part of the development of a self propulsion modelling framework in the open source software package OpenFOAM. Ultimately, the goal is to acquire efficient numerical tools for modelling self propulsion in waves of realistic hullforms as well as propeller-rudder interaction.

2 Self propulsion framework

Modelling propulsion of a ship travelling in waves requires some form of control regulating the balance between hydrodynamic loads on the hull and the thrust and torque generated by the propeller. For this reason, a control framework has been created for OpenFOAM with three purposes:

- To determine/control the propeller RPM
- To handle information exchange between the flow solver, the propeller model and the dynamic mesh solver
- To have a modular definition of the propeller model and control function

2.1 Modular system

The last purpose is added to allow for an easy expansion of the framework. The definition of the propeller model as well as the control function is made as a selectable option. This means that the definition of the propeller model is independent of the information exchange. To introduce a new propeller model, a user would only have to clone an existing one, rename it and change the code to have a new selectable option for propeller modelling. The information exchange of the framework is shown in Figure 1.

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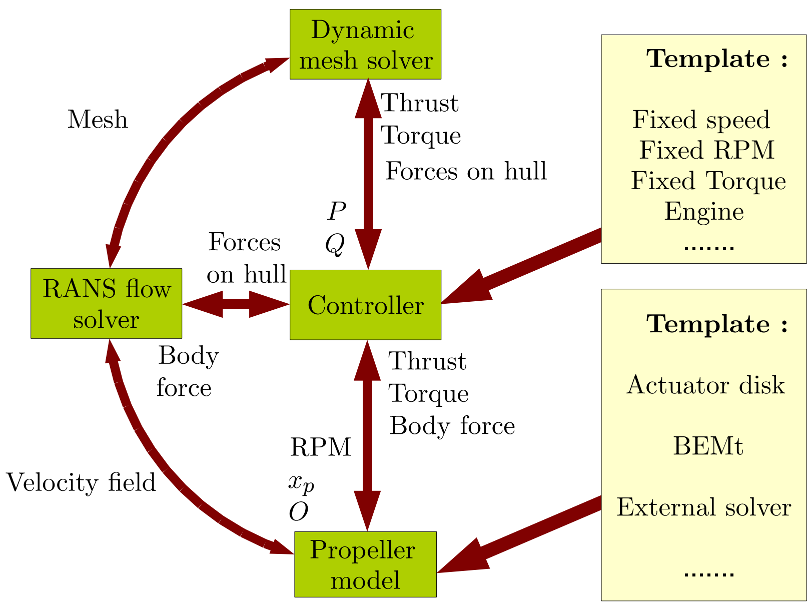

Figure 1: Self propulsion framework for OpenFOAM

3 Ship motions and cell identification

The ship motions in this model are based on forces and moments acting on the hull (including the propeller thrust and torque) and the equations of motion for a rigid body in 6 DOF. The forces and moments calculated with the RANS modelling technique used here were validated against experiments for a fixed hull in waves by Windén et al. (2012). The body force due to the propeller is introduced as an extra term in the unsteady RANS equation and is non-zero only in those cells which lie within the extent of the propeller disk. This means that these cells and their relative location within the propeller disk needs to be known.

The mesh is deformed using a Laplacian function on node displacement and keeping the moving hull and the domain edges as rigid boundaries as described by Jasak and Tukovic (2007) and Jasak (2009). The motion of points is diffused based on the inverse distance from the hull. This means that cells close to the hull are practically moving as part of the rigid body to ensure minimal distortion of boundary layer cells and other important mesh features near the hull. It also means that the body force distribution in the mesh should stay mostly constant since the cells inside the propeller disk are relatively close to the hull. They should therefore mostly move as part of the rigid body for moderate motions. Despite this, in the interest of developing a more generalised method, the cell identification process to determine where the body force should be added is handled and updated in run-time.

3.1 Relative location handling

The position of the propeller centroid x_p, the orientation of the propeller disk $O = (O_1, O_2, O_3)$ for an arbitrary ship orientation (defined by the rotation tensor Q and the offset P) is shown in Figure 2 and are calculated using the original centre of gravity CG_0 and the original orientation tensor O_0 as

$$xp = CG_0 + P + Q \cdot (xp_0 - CG_0) \tag{1}$$

$$O = Q \cdot O_0 \tag{2}$$

The the relative position of a cell I with its centroid located at coordinate x_I is given as

$$R_I = \begin{bmatrix} O_2^2 + O_3^2 & -O_1O_2 & -O_1O_3 \\ -O_1O_2 & O_1^2 + O_3^2 & -O_2O_3 \\ -O_1O_3 & O_2O_3 & O_1^2 + O_2^2 \end{bmatrix} (x_I - x_p) \tag{3}$$

$$d_I = (x_I - x_p) \cdot O \tag{4}$$

Here, R_I is the radius from x_I to the propeller axis and d_I is the distance from x_I to the propeller centre plane (Windén et al., 2013). Using this definition, active cells can be identified as fulfilling $r_H < R_I < R$ and $d_I < d/2$ where R is the tip radius, r_H is the hub radius and d is the disk thickness.

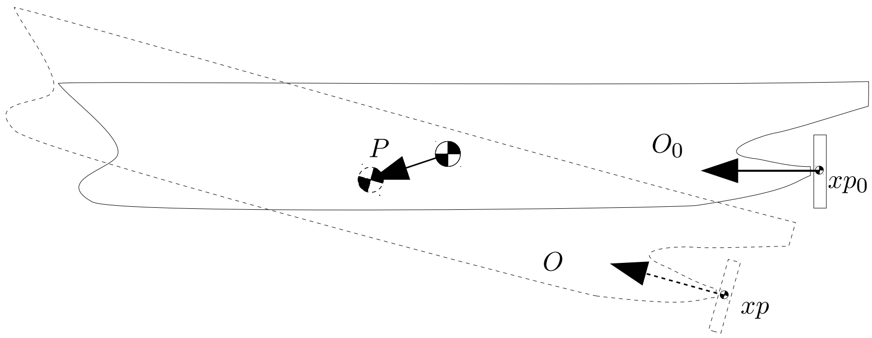

Figure 2: Movement of propeller region due to arbitrary ship motions

4 BEMt propeller model

In this paper the use of the BEMt approach in the self propulsion framework is studied. Blade element momentum theory combines both the blade element theory and the momentum theory. The combination of these two theories alleviates some of the difficulties in calculating the induced velocity of the propeller. Solution to this problem can be achieved if the part of the propeller between radial elements r and $(r+\delta r)$ is analysed by matching forces generated by the blade elements, as 2D lifting foils to the momentum changes occurring through the propeller disc between these radii. An actual propeller is not uniformly loaded as assumed by Rankine and Froude actuator disc model, thus to analyse the radial variation of loads along the blade, it is ideal to divide the flowfield into radially independent annulus stream tubes. Here, an existing BEMT model, (Molland and Turnock, 1996) was modified and coupled with a RANS solver. The BEMt code is applied on a separate concentric structured mesh and the resulting thrust and torque distribution is mapped onto the RANS mesh using trilinear interpolation. This is done so that the structure of the RANS mesh at the stern can be made independent of the sectoring in the BEMt code. However, care must be taken so that the both meshes have similar levels of refinement to avoid poor interpolation performance.

4.1 Propeller Open water characteristics

The open water performance shown in Figure 3 calculated from the BEMt code is compared with values provided by Molland and Turnock (2007), and that of Badoe et al. (2012) who carried out similar investigation on the same propeller using an Arbitrary Mesh Interface method (AMI). The agreement for KT was good with difference of less than 1% between both models. The trends with varying advance ratios are also well predicted.

Variations in KQ also showed under prediction for the BEMT model. CFD solutions over or under predict torque, and discrepancies increases with increasing propeller advance coefficient, J, when using a propeller model based on the momentum theory. This tendency seems to be prevalent in the open water plot below. This has also been reported by Uto (1993) who carried out RANS simulations involving marine propellers. These over predictions might be unavoidable due to experimental conditions such as tunnel wall, inflow speed nonuniformity and hub and boss configurations which do not conform to CFD simulations.

4.2 Computational effort

An important factor governing the choice of propeller modelling technique is the computational effort. Table 1 compares the associated cost in computation for a propeller-rudder interaction study by Badoe et al. (2012) and Phillips (2009) using an AMI, an actuator disk model and the BEMt model. It is clearly seen here that the BEMt and the actuator disk is far superior to the AMI approach in terms of computational effort.

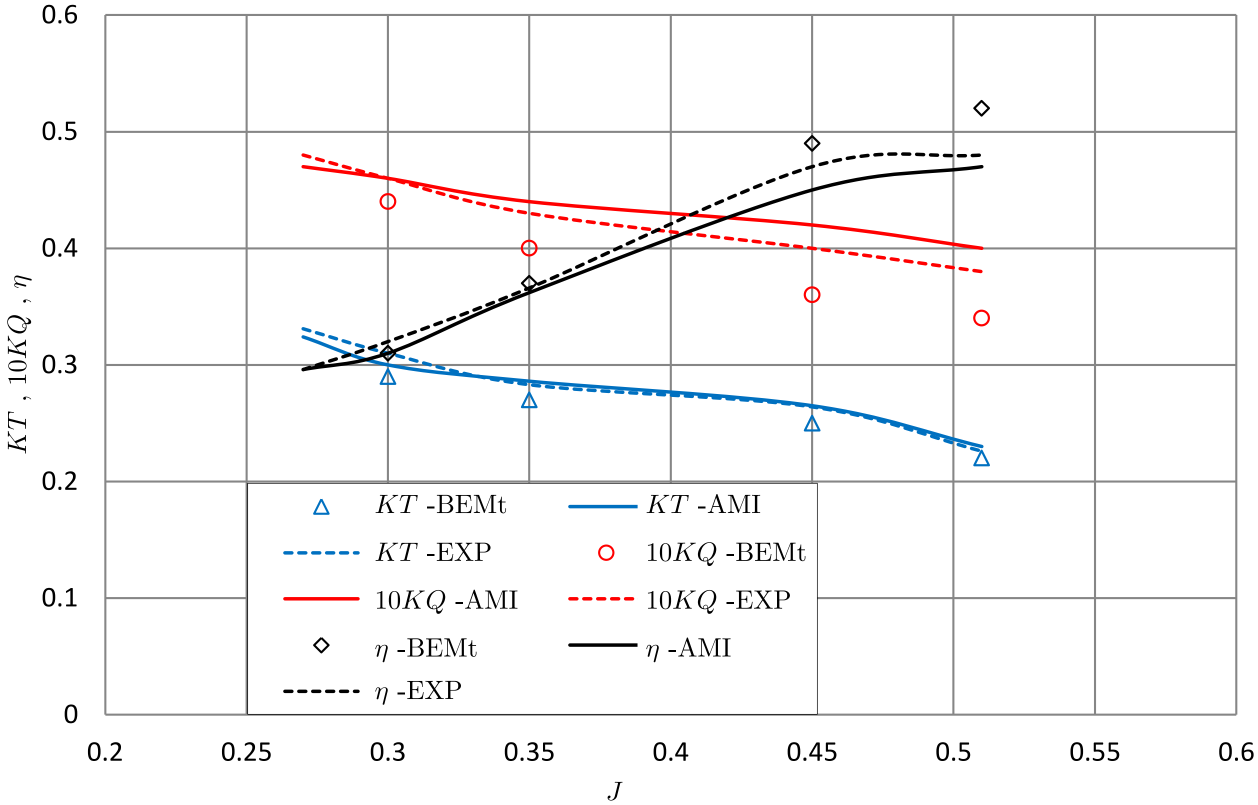

Figure 3: Comparison of propeller characteristics in open water. Experimental data by Molland and Turnock (2007).

Table 1: Computational cost comparison between different propeller modelling alternatives

Parameter	AMI Propeller	Actuator disk model	BEMt model
Mesh size	4-6M	4-6M	4-6M
Computer	Iridis 3 Linux Cluster	Iridis 3 Linux Cluster	Iridis 3 Linux Cluster
Resources utilised	6x8 processors	6x8 processors	6x8 processors
Simulation time	20-22 h	1.5-2.5h	3-4 h

5 Determination of wake fraction

The success of the body force approach relies on how accurately the relation between the ship wake and the propeller performance can be modelled. The unsteadiness of the nominal wake of a ship travelling in a seastate inevitably affects the thrust and torque delivered by the propeller and thus the self propulsion performance of the ship (Molland et al., 2011). This means that changes in the propeller inflow due to ship motions, passing waves and unsteady flow separation at the stern must be taken into account in the model. The propeller advance velocity can be easily corrected for ship motions through the movement of the ship centre of gravity and the global rotation tensor as shown in Figure 2. However, the variations in the wake due to waves, separation and motions can only be captured by probing the propeller inflow velocities in run-time.

The local advance coefficient is defined as

$$J_{local} = J(1 - wt) \tag{5}$$

where wt is the local wake fraction obtained from the probed velocities.

5.1 Probe locations

For each cell node in the BEMt mesh, an estimate of the local inflow condition is needed to determine local advance ratio. Considering the fact that the propeller might be tilted relative to the freestream, the probe location should be somewhere along a line parallel with the normal vector to the propeller disk. This way, if the propeller is tilted, only the component of the inflow velocity that is parallel with the propeller axial direction will be considered as the axial wake, the rest would be considered as tangential wake components. Furthermore, it has to be decided where along this line the probing should take place. The possible positions for probing the inflow velocity for a node i is shown in Figure 4.

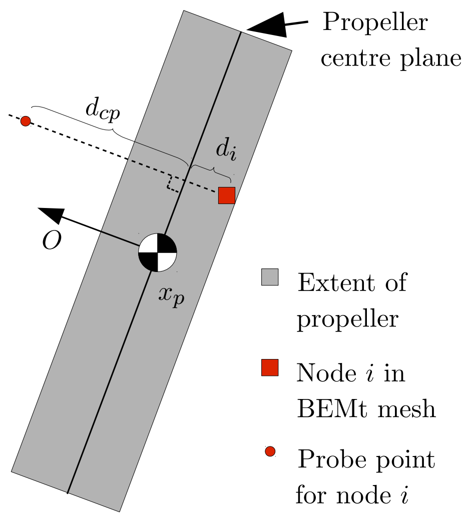

Figure 4: Location of probing point for node i in the BEMT mesh

The probe point x_{probei} can be found as

$$x_{probei} = x_i - (d_{cp} + d_i)O \tag{6}$$

The velocity at this point is obtained by trilinear interpolation from the RANS mesh to the BEMt mesh. By using an active probing of the velocity field in run-time, both the axial and tangential components of the wake can be considered something that will add more realism to the thrust and torque distributions (Molland et al., 2011). Several options are available for the location of the probes, Rijpkema et al. (2013) showed that the thrust and torque obtained from coupling RANS with a Boundary Element Method (BEM) for modelling the propeller is dependent on the location of the location of probing. Furthermore, depending on where the probe point is chosen, there may or may not be a need to correct the probed velocities for the axial and circumferential inflow factors a and a'.

6 Results

Results are shown here for the self propelled KCS container ship in head waves ($\lambda/Lpp = 1$)at low speed ($Fn = 0.05$.) The probe location is chosen as $d/2$ in front of the propeller front face. The propeller induced velocities at this location are relatively low so no correction is made for a and a' to improve stability. A start RPM of 300 is chosen and, to improve stability, a limiter of 10 RPM/s is set on the RPM variation given by the controller. Figure 5 shows the velocity field, the active volume force region and the free surface around the hull in waves. Figure 6 shows the evolution of RPM and forward speed in waves and calm water. Figure 7 shows the evolution of the thrust and torque coefficients.

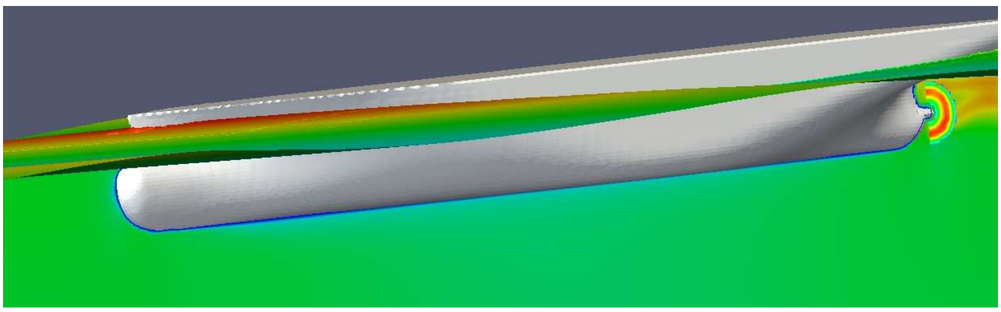

Figure 5: Self propelled KCS in head waves

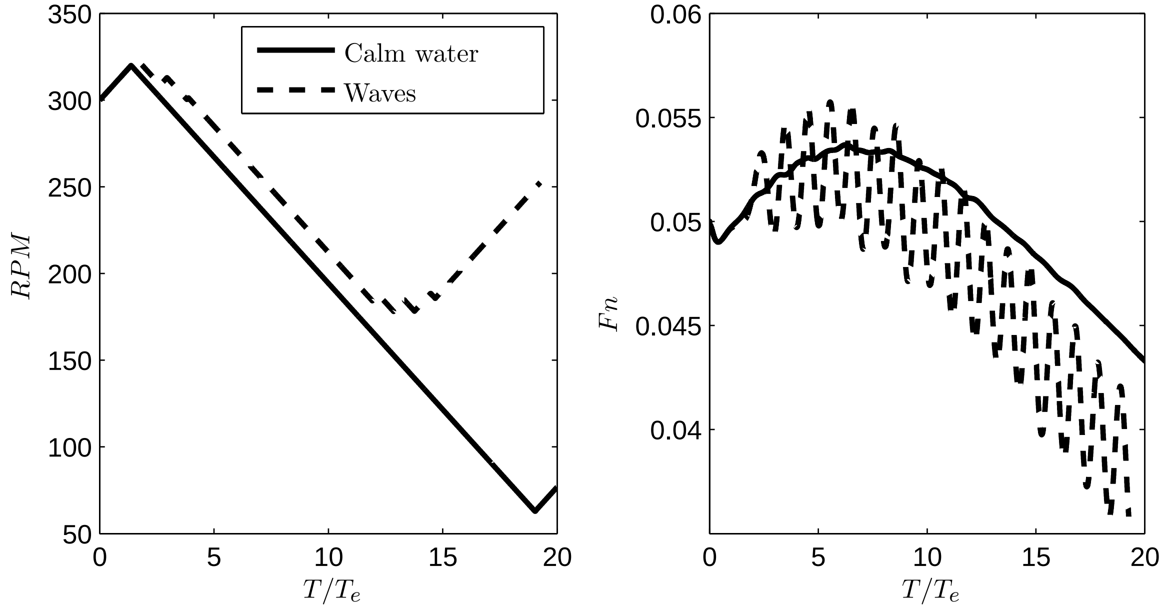

Figure 6: Evolution of RPM and forward speed in waves and calm water for self propelled KCS

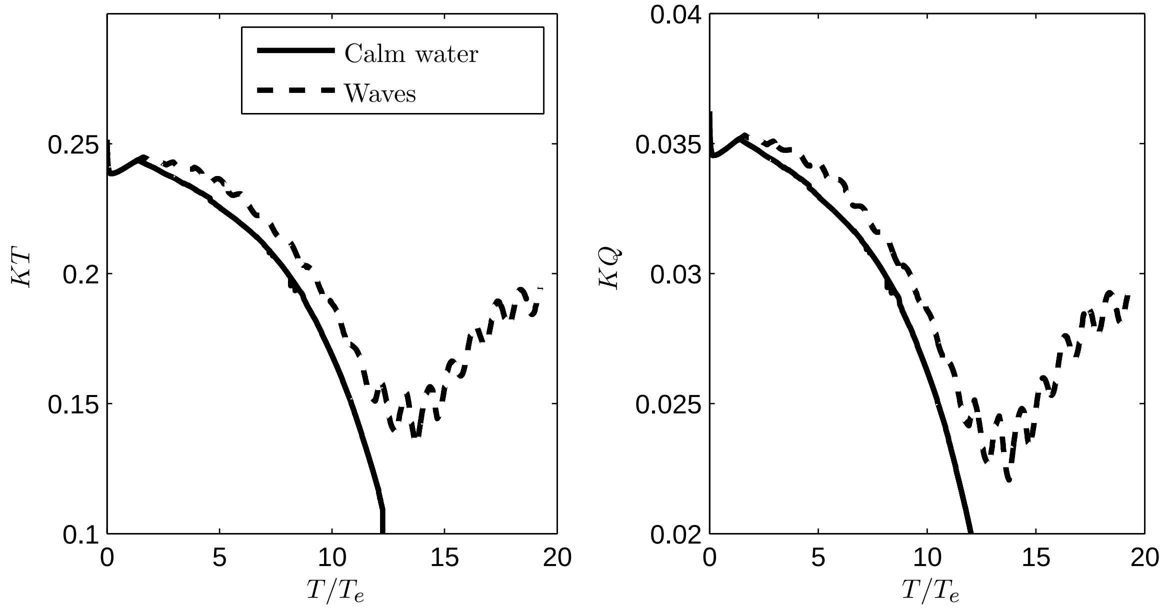

Figure 7: Evolution of coefficients of thrust and torque in waves and calm water for self propelled KCS

It can be seen in Figure 6 that the initial RPM was set too high. This results in an initial increase in forward speed, the controller has overcompensated for this with a large drop in RPM which caused the propeller to stall at $T/T_e = 12$ in the calm water case. In waves, the added resistance meant that the controller increased the RPM before the point of stall leading to a better evolution of KT and KQ.

These initial results have indicated that the described modelling technique has much merit for capturing many aspects of self propulsion in waves. However, better initial conditions are needed to make the simulations more realistic. There is much scope for detailed future studies on the influence of the controller algorithm, the location and method for probing the local advance coefficient. In these simulations the propeller modelling, including all cell identification, probing and mapping took up $\approx$0.4% of the total computational time for each time step which reinforces the efficiency savings that can be achieved by using a BEMt compared to direct modelling of the propeller geometry.

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