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Influence of drift angle on the computation of hull–propeller–rudder interaction

Charles E. Badoe*, Alexander B. Phillips, Stephen R. Turnock

Fluid Structure Interactions Research Group, Faculty of Engineering and the Environment, University of Southampton, Southampton SO17 1BJ, United Kingdom

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ABSTRACT

The operation of the propeller dominates the flow interaction effects on the upstream hull and a downstream rudder. An investigation is carried out into the sensitivity with which these effects can be resolved when an angle of drift is applied as well as the length of an upstream body is varied. The computed results are compared to a detailed wind tunnel investigation which measured changes in propeller thrust, torque and rudder forces. Variation of the upstream body length and drift angle effectively varies the magnitude of the crossflow and wake at the propeller plane. The time resolved flow was computed around the hull–propeller–rudder configuration using the Reynolds-averaged Navier–Stokes (RANS) equations and an Arbitrary Mesh Interface (AMI) model to account for the motion of the propeller. A mesh sensitivity study quantifies the necessary number of mesh cells to adequately resolve the flow field. Overall, good agreement is found between the experimental and computational results when predicting the change in propulsive efficiency, flow straightening and rudder manoeuvring performance. However, it can be seen that there is a significant computational expense associated with a time resolved propeller interaction and that alternative body force based methods are likely to still be required with the computation of self-propelled ship manoeuvres.

1. Introduction

Accurate determination of rudder forces when a ship is operating at an angle of drift is a necessary condition for the accurate computation of a ship manouevre and its coursekeeping ability. Similarly, the propulsive efficiency effects of drift and rudder angle could be important in determining the overall effectiveness of energy efficiency devices. Rudder forces are strongly influenced by the interaction between the forces and moments generated on the hull and propeller upstream of the rudder. One fundamental criterion in which the rudder forces depends is the effective rudder angle (Molland and Turnock, 1995). When course change is applied using the rudder, the flow of water is no longer aligned with the hull but develops a crossflow across the propeller plane. This will alter the propeller thrust and torque as well as changing the effective direction of the propeller race. The net sideforce due to the propeller will now vary than that during straight ahead conditions resulting in a decrease in effective inflow angle to the rudder. At the same time the propeller and hull upstream of the rudder also straightens the flow leading to a recovery in the effective inflow angle to the rudder. Flow straightening effects therefore play an important role in the accurate determination of rudder forces during ship manoeuvring. A number of studies, including those of Yumuro (1974, 1975, 1978), have been conducted to examine the effect of drift angle and flow straightening influence of the combined hull and propeller on the rudder. The influence of drift angle on forces and moments as well as trim and sinkage has also been studied for a cargo/container ship (Longo and Stern, 2002). Kijima et al. (1995, 1996a, 1996b) investigated the hydrodynamic forces acting on a hull in oblique flow conditions. Abramowski (2005) studied the forces on the propeller during ship manoeuvring. Yasukawa et al. (1996) presented a methodology of calculating the hydrodynamic forces on a ship moving with constant rudder angle. Phillips et al. (2009) investigated the manoeuvring coefficients of a self-propelled ship at drift by coupling a propeller performance code based on the blade element momentum theory to a Reynolds averaged Navier Stokes flow solver. El Moctar (2001) applied a finite volume method to viscous flow calculations on a ship's hull and presented the hull forces as a function of drift angle. Jurgens (2005) assessed the maneuverability and controllability of fast planning monohulls by comparing the outcome of tests at angles of drift with results from rudder deflection test to determine the flow straightening effect of the hull on rudder.

However, few works have been reported on the flow straightening influence of the propeller independently on the rudder. One

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* Corresponding author at: Fluid Structure Interactions Group (Building 28/1021), Faculty of Engineering and the Environment, Highfield Campus, University of Southampton, Southampton SO17 1BJ, United Kingdom. Tel.: +44 23 8059 5097.
E-mail addresses: cb3e09@soton.ac.uk (C.E. Badoe), abp@soton.ac.uk (A.B. Phillips), s.r.turnock@soton.ac.uk (S.R. Turnock).

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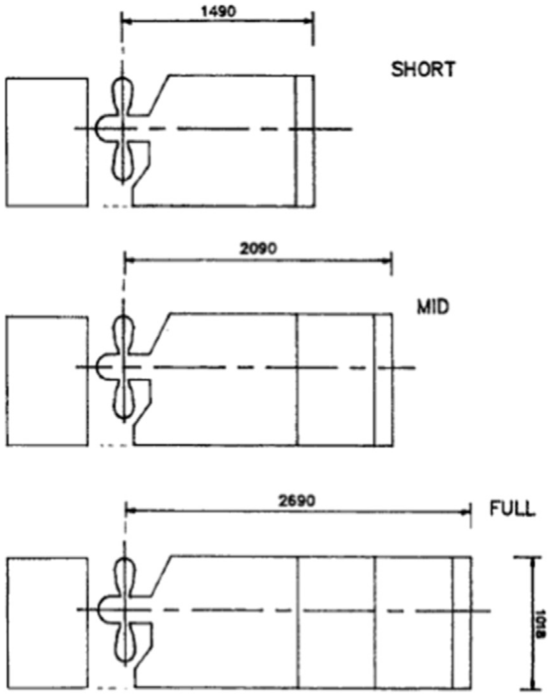

Fig. 1. Overall dimensions of three centerboard configurations, *source*: Molland and Turnock (2007).

such investigation was carried out by Molland and Turnock (1995) who examined the flow straightening influence of the propeller on the effective angle of drift at the stern and how it alters the performance of the rudder. Simonsen (2000) and Phillips et al. (2010) followed on the work by Molland and Turnock (1995) by providing insight into the interaction between the propeller and rudder at straight ahead conditions using CFD methodologies.

This paper aims to replicate numerically the work carried out by Molland and Turnock (1995) by providing detailed insight into the interaction between the propeller and rudder, flow field information, pressure distributions on the rudder surface and the contribution of thrust and torque augment on the propeller blades for:

- a propeller–rudder combination with and without applied angles of drift.
- centerline boards of different lengths (Fig. 1) situated upstream of the propeller–rudder combination at drift to simulate the influence of an upstream centreboard on flow straightening.

It has been argued by Molland and Turnock (1991, 2002) that for a propeller upstream of a rudder, a good approach to model the physics involved is to treat the rudder and propeller as a combined unit. The influence of drift angle can then be applied in the form of velocity and flow straightening inputs to the basic isolated model of the rudder propeller combination. By using such approach, data for the rudder and propeller can be applied downstream of a hull, provided the hull wake fraction and hence the appropriate inflow velocity is applied to the rudder–propeller combination.

The terminology applied to the flow straightening in the present study is illustrated in Fig. 2, where δ is the rudder angle relative to ship axis, β_R is the geometric drift angle at the rudder which is larger than the ships drift angle β on a turn. For a model test in wind tunnel or towing tank β_R is the same as β.

With no flow straightening due to the propeller, the geometric rudder angle α, is given by:

$$\alpha = \delta - \beta_R \tag{1}$$

With flow straightening due to the propeller, the effective rudder angle α_E, is given by:

$$\alpha_E = \delta - \alpha_0 = \delta - \gamma\,\beta_R \tag{2}$$

where γ is the flow straightening factor which depends on drift angle and propeller loading, and α_0 *is* the incidence for zero lift and can be obtained from basic lift and drag data (Molland and Turnock, 1995).

2. Case description

The cases considered are based on wind tunnel tests performed by Molland and Turnock (1995) at the University of Southampton 3.5 m × 2.5 m wind tunnel. The experimental set-up comprises of a 1 m span, 1.5 geometric aspect ratio rudder based on the NACA 0020 aerofoil section (rudder no. 2). A representative propeller based on the Wageningen B4.40 series was used. The propeller is four bladed, with a diameter of 0.8 m. The rudder geometry and its arrangement with respect to the propeller are given in Fig. 3. Dimensions of the different length of centerline boards are also shown in Fig. 1. Simulations were carried out for a constant wind speed of 10 m/s and propeller revolutions of 2100, 1460 and 800 rpm, corresponding to propeller advance coefficients, $J=0.36$, 0.51 and 0.94, respectively, which covers the operating conditions of most vessels. The propeller P/D at 0.7R is 0.95 and the rudder–propeller separation was fixed at $X/D=0.39$. The rudder was mounted on the propeller centerline corresponding to $Y/D=0$ with maximum height of the propeller tip coincident with the rudder tip at 1 m.

Five sets of simulations were carried out:

i. a propeller rudder combination in isolation at straight ahead conditions, that is without the application of drift angle for geometric rudder angles $\alpha=-10.4^\circ$, -0.4° and 9.6°.
ii. a propeller rudder combination at drift angle of -7.5° for geometric rudder angles $\alpha=-10.4^\circ$, -5.4°, -0.4°, 4.6° and 9.6°. In relation to ship axis the geometric rudder angles will correspond to $\delta=-17.9^\circ$, -12.9°, -7.9°, -2.9° and 2.1°.
iii. a short centerline board with propeller and rudder at drift angle of -7.5° for geometric rudder angles $\alpha=-10.4^\circ$, -0.4° and 9.6°.
iv. a medium centerline board with propeller and rudder at drift angle of -7.5° for geometric rudder angles $\alpha=-10.4^\circ$, -0.4° and 9.6°.
v. a long centerline board with propeller and rudder at drift angle of -7.5° for geometric rudder angles $\alpha=-10.4^\circ$, -0.4° and 9.6°.

Full details of the geometrical parameters of the propeller, rudder and centerboard and simulation flow conditions are presented in Tables 1 and 2, respectively. It should be noted that the drift angle simulations were carried out in propeller (+Hull) axis but the rudder results are presented in terms of wind tunnel axis (geometric inflow direction).

3. Numerical method

3.1. Governing equations

The flow generated around the propeller rudder and centerboard configurations at drift can be modeled by the unsteady Reynolds averaged Navier–Stokes equations. Within the assumption of an incompressible fluid, the set of equations may be written