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Practical computational procedures for predicting steering and braking forces of escort tugs

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ABSTRACT

Two distinct computational procedures based on semi-empirical and Reynolds-Averaged-Navier-Stokes (RANS) computations are presented to estimate towline forces applied by tractor type escort tugs. The crucial part of both techniques is to calculate the hydrodynamic forces generated by the hull and appendages of the escort tug. The escort performance is characterised by the components of the towline force, namely steering and braking forces, which can be estimated easily from the quasi-static equilibrium condition. In the semi-empirical approach, the hydrodynamic forces are represented by a set of manoeuvring derivatives, which are obtained by regression equations based on model test measurements or full-scale test results. This technique is quite simple and only requires basic design parameters but ignores the details of the hull and appendage geometries and only suitable to be used for the yaw angles up to the stall angle. The RANS-based approach, however, is complex and requires detailed hull and appendage geometries but takes the local flow characteristics into consideration. These techniques are proposed to be used at the different stages of the design process depending on the availability of hull and appendage data.

1. Introduction

The high volume of traffic in confined waterways such as the Strait of Istanbul (Bosphorus) increases the possibility of collisions and groundings with major consequences including loss of lives and environmental disasters. Most of the collisions and groundings are caused by a loss of engine power and/or rudder control and could be prevented by emergency steering provided by adequate tug escort. Simulator studies and actual experience in many ports and channels around the world have proved that tugs of suitable design and power are able to significantly assist in the control of laden tankers in the event of a loss of propulsion or steerage, when running connected at the stern of the vessel (OCIMF, 1997).

In order to reduce the risk of ship groundings and collisions, the Turkish Straits Vessel Traffic Service (TSVTS) requires that large vessels, particularly those loaded with dangerous cargo, shall be escorted by suitable type, size and number of escort tugs. This requirement is widely considered to result in a positive improvement to the safety of navigation (OCIMF, 2007). However, in some particular cases, the ship operators argue that the decision about the type and number of escort tugs are taken by TSVTS mainly depending on the tug operators' experiences.

It is now widely accepted that escort tugs are the most effective way of reducing the risk of ship groundings and collisions when a large vessel loses the engine and/or rudder control in confined waters. While the performance of conventional tugs could be represented by a single measure (bollard pull), which is mainly related with the engine power, the performance of escort tugs depends on many factors including the hull and skeg geometry, the location of the propellers and the towing staple, and the stability characteristics.

The grounding of large tankers, with dramatic environmental consequences, has resulted in the emerging of research programs for designing escort tugs that are capable of rendering effective braking and steering assistance to large tankers operating in restricted waters (Dabbar and Morgan, 1996; Hensen, 1997; Hutchison et al., 1993; Jagannathan et al., 1995; Sturmhöfel and Bartels, 1993). One of the earliest of these research programs included planar force model tests with a 7200 bhp tractor tug design. A significant finding from these tests was that the hydrodynamic interaction was small between the flow around the hull and the propeller induced flow. This finding enabled the development of escort performance simulations based on equilibrium conditions on the horizontal plane (Hutchison et al., 1993).

An extensive model test program was conducted by Allan (2000) to investigate a series of hull forms and associated appendages which can

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be adapted to escort tugs with either cycloidal or azimuth stern drive propulsion to develop an efficient escort tug design with a capability of generating 150 tons of escort steering force. Initial tests indicated that the predicted forces could not be achieved, mainly, due to a shift to the aft in the position of the centre of lateral resistance (CLR) through the significant angles of attack. To meet the design target steering force, the design of the skeg was increased and the CLR shifted forward by about 2%. The second series of tests were then performed on the modified skeg design, which showed that at 10 knots the tug can obtain a maximum steering force of 150 tons.

Molyneux (2003) conducted further tests with a 1:18 scale model of the same tractor type escort tug design to obtain lift and drag forces for the hull in combination with different appendages, which included the case of the hull with and without the fin. The range of ship speeds was from 4 to 12 knots (with model speeds based on Froude scaling). The model was fixed at the required yaw angle and the measurements were made of surge force, fore and aft sway forces and yaw moment using a Planar Motion Mechanism (PMM). The model was free to roll about the axis through the towing staple and free to pitch and heave. At the high speeds of 10 and 12 knots, yaw angles tested varied from a small negative value to approximately 45°. For speeds of 4, 6 and 8 knots, yaw angles varied from a small negative value to 105°. It was concluded that the free surface wave effects were small for the range of speeds typically found in escort tug operation.

Allan and Molyneux (2007) presented the results of scaled model experiments with three different type of escort tugs representing Voith tractor, Azimuth Stern Drive (ASD) and Z-drive tractor. 1:18 scaled models of each tug were constructed. The aim of these experiments was to measure the hydrodynamic forces and moments generated by the various hulls and appendages. No propulsion units were fitted and a wide range of yaw angles likely to be encountered during escort operation was covered. The models were fixed at a given yaw angle during the tests and measurements made for the surge and sway forces and yaw moment, for the range of operating speeds and yaw angles. The speeds tested corresponded to 4, 6, 8, 10 and 12 knots in full-scale. The steering and braking force coefficients and the position of the centre of lateral resistance were measured and compared for different types of tugs.

Model tests have proven to be extremely useful in designing hull and appendages of escort tugs. However, excessive time and cost requirements have limited their applications in the early stages of the design process. The emergence of computational fluid dynamics (CFD) has provided designers a more practical tool to facilitate early design performance studies.

Molyneux (2007) and Molyneux and Bose (2008) used a commercial Reynolds-Averaged-Navier-Stokes (RANS) solver with $k-\omega$ turbulence model to predict the forces and flow patterns around the hull of a 39-m Voith tractor type escort tug. The predictions were compared with data from model experiments with a PMM conducted by Molyneux (2007). A hexahedral mesh was found to be most suitable for predicting the escort forces resulting in calculated forces that on average were within 5–6% of measured values and never exceeded 10%. The largest discrepancy occurred at high yaw angles of 60°. The study neglected the free surface effects on the basis that the effect of the free surface on the forces measured in the model experiments were small.

Jahra et al. (2015) also investigated the hydrodynamic forces and moments of the same escort tug at steady oblique flow conditions using a commercial RANS solver with$k-\varepsilon$ turbulence model. The free surface was modelled using the Volume of Fluid (VOF) approach for calm water condition. The hull was assumed fixed in space with an even keel. The RANS solver predictions were compared with the experimental measurements at 15°, 30° and 45° yaw angles. At 15° and 30° flow conditions, a reasonable agreement between the measurement and the predicted results was achieved but it was found that the RANS solver prediction underestimated the sway forces for the 45° heading. This was considered to be due to the turbulence model used in the computational method, which was not suitable for predicting the highly separated flows observed at yaw angles of approximately 30° and higher.

Smoker et al. (2016) used commercial viscous flow solver package with $k-\varepsilon$ turbulence model to predict lift and drag forces at large yaw angles of the same escort tug model used by Molyneux (2007). In these simulations, the model was free to heave but was set at a fixed roll angle. A range of simulations was performed for yaw angles ranging from 0° to 45° and calculated lift and drag forces were compared against escort model tests. The computational results for maximum lift were within 2% of the experimental values with the same stall angle of approximately 37° predicted in both cases. The calculated drag force was consistently within 10% of the model test values; however, the CFD simulations increasingly underpredicted the drag force as the yaw angle increased. Once flow separation had occurred above about 37°, the predicted lift and drag forces were significantly below the model test forces.

Reliable estimation of hydrodynamic forces by model tests or computational methods enabled the development of numerical models to estimate the escort performance characterised by the steering and braking forces applied by the tug (Waclawek and Molyneux, 2000; Ratcliff, 2003). These numerical models, in general, are based on basic design characteristics related to the tug's hull, appendages and the propulsion parameters. In these models, in general, the hull, appendages and thrusters are considered separately and the interactions between them are omitted due to the difficulties in dealing with the complex flow characteristics around the tug, particularly at higher speeds and large yaw angles.

To investigate the interaction between thrusters, Brandner and Renilson (1998) conducted a series of experiments and measured the forces acting on two thrusters for a range of relative positions. The results showed that forces from the trailing thruster are heavily affected by interaction, particularly due to impingement of the race from the leading thruster, whereas forces from the latter remained essentially unaffected despite its proximity to the former. A major contribution in the prediction of the performance of vertical axis propellers in escort conditions is due to Molyneux and Waclawek (2001) in which regression equations were presented enabling practical estimation of the effective thrust force and its direction.

Bilici et al. (2016), presented two distinct computational methodologies, based on semi-empirical and RANS based approaches, to practically estimate the maximum achievable steering and braking forces depending on the escort tug configuration as well as the type and speed of the escort operation. In order to validate the hydrodynamic force calculations, model test results of a Voith Schneider Propeller (VSP) equipped tractor type escort tug "Ajax", presented by Molyneux (2007), were used. Comparison of these measurements with those predicted by the semi-empirical and RANS based computational methodologies indicated that both procedures provide an acceptable level of correlation, particularly at the lower range of yaw angles.

This paper presents a further and extended application of the above-mentioned study (Bilici et al., 2016), which was based on limited tug geometric particulars available in the open literature, to test the predictive capability of the semi-empirical and RANS based methods with an escort tug configuration representing state-of-the-art design features. It is shown that the steering and braking forces generated by an escort tug can be determined by using the components of the thrust force and the hydrodynamic forces, i.e. the lift and drag forces. Therefore, the crucial part of the methodology is to predict the hydrodynamic forces due to the tug's hull and skeg. The hydrodynamic hull forces can easily be estimated by a set of manoeuvring derivatives, which are obtained by reliable semi-empirical methods based on model test measurements or full-scale test results. The lift and drag forces due to the skeg can also be estimated by empirical methods based on experiments conducted with low aspect ratio wing sections. However, this semi-empirical approach is basically suitable to be used for the yaw angles up to the stall angle and ignores the effect of local flow characteristics. Hence, these