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ABSTRACT

Vertical Axis propellers have been widely accepted as a propulsion system for tugs because they provide several advantages over screw propellers. The principle attraction is their ability to vary thrust magnitude and direction, whilst maintaining a constant engine rotation rate. When applied to tug designs, the propellers are typically positioned so that they extend beyond the keel. This has the advantage of keeping the propellers in unobstructed flow, but has the disadvantage of placing them in a vulnerable position, which is normally compensated for by the addition of a protective cage. This type of propulsion system has been widely accepted for escort tugs, which use forces generated at high speeds and large yaw angles to control a tanker in an emergency situation.

There has been very little data published on propeller performance when the force direction is not aligned with the direction of ship motion. As a result, it is difficult to understand all the factors affecting escort tug performance. During the course of a project to simulate the performance of an escort tug, model experiments were carried out to measure the performance of the tug's hull and its vertical axis propulsion system. These data showed that the amount of force generated by the propulsion system varied significantly with the angle of the propeller thrust direction relative to the incoming flow. In order to make the model data useful for future numerical simulations, predictor equations, based on design variables were developed. Equations were used to predict the force created by the propulsion system, the direction in which it acted, the total torque absorbed by the propellers and the proportion of the torque absorbed by port and starboard propellers. This paper compares the results of the experiments with the predictor equations and discusses the trends in the data, together with some of the implications for the application of vertical axis propellers to escort tugs.

NOMENCLATURE

D	Propeller diameter, m
Fd	Force developed by propulsion system, N
F_x	Component of Fd along tug centerline, N
F_y	Component of Fd normal to tug centerline, N
J	Advance coefficient, V/nD
Kfd	$Fd/\rho n^2D^5$
Kq_{total}	$Q_{total}/\rho n^2D^5$
n	Propeller rotation, sec^{-1}
Q_{port}	Torque absorbed by port propeller, N-m
Q_{total}	Torque absorbed by port and starboard propellers, N-m
V	Speed, m/s
β	Yaw angle, relative to tank centerline, deg.
δ	Thruster angle, relative to tug centerline, deg.
γ	Dynamic thrust angle, relative to tug centerline, deg.
ι	Static inflow angle, relative to tank centerline, $(\delta-\beta)$ deg.

INTRODUCTION

The operation of large tankers in crowded or confined environmentally sensitive waterways has increased the demand for escort tugs. The role of the tug is to keep the tanker under control, should it experience a failure of its propulsion or steering system. This can take the form of braking, accelerating the rate of turn or correcting the course of the tanker. The challenge for the tug is to be able to assist the tanker in an emergency, without compromising its normal operation. If the environmentally sensitive region is extensive, then there is a serious economic impact to the tanker if it reduces speed unnecessarily. Therefore the tug has to be capable of safely taking control of the tanker at speeds up to 12 knots, well beyond the safe operating capability of harbour tugs. Escort tugs have been used in Puget Sound and on the approach to the Valdez terminal (Alaska) for many years and are being introduced in Placentia Bay, Newfoundland, for tankers associated with the Hibernia oil development and the Come-By-Chance oil refinery.

The escort tug is attached to the tanker by a towrope, and uses the hydrodynamic forces generated by the hull and propulsion system to generate steering and braking force components. At 10 knots, the tug can typically generate up to 2.5 times its bollard pull by using 'indirect' mode, where the hull is held at a high yaw angle (40 to 50 degrees) by an azimuthing propulsion system. This requires the tug to remain stable and under control with a large component of this load normal to its centreline. With a single towline between the tanker and the tug, the operational practice is to vector the thrust to balance the yaw moments created between the hull force and the towline tension. The degree of steering and braking force is controlled, to some extent, by the direction of the propulsion vector. When the propulsion vector is directed between 30 and 40 degrees to the tug's centreline, the tug generates a high steering force component with a small braking force component. When the propulsion vector is oriented at approximately 120 degrees to the centerline of the tug, it generates a large braking force and a small steering force.

At low speeds, 6 knots and under, the hydrodynamic forces created by the hull becomes much smaller, in relation to the forces created by the propulsion system at full power. As a result, the tug tends to align with the towrope as in a conventional assist. This mode of operation is referred to as direct mode.

The accepted measure of performance for escort tugs is a graph of maximum braking force plotted against maximum steering force, for a given speed. This can be obtained from overload style propulsion experiments with a model of the hull and its propulsion system. However, the resulting test matrix can be large, for the full range of speeds and thruster angles. It is therefore desirable to be able to simulate the tug's performance in escort mode, rather rely entirely on the results of experiments. The Institute for Marine Dynamics (IMD) developed a simulation method for predicting the track of a tanker assisted by an escort tug, which used numerical predictions of the tug's performance (Waclawek and Molyneux, 2000). The simulation assumes that the forces created by the hull and the propulsion system can be predicted separately and combined to give the prediction of the total force. Whilst the method gave good predictions for maximum steering force, it was less successful at predicting maximum braking force. One of the initial assumptions in the simulation was that the propulsion force was independent of its orientation relative to the incoming flow. This assumption was made based on conclusions from earlier work (Hutchisson et al, 1993). It was also the simplest option to incorporate into the simulation. However, some preliminary analysis, based on a set of model data for a specific tug tested at IMD, suggested that this assumption was not strictly true. It was the desire to obtain a better understanding of the variation in the magnitude of the propulsion force vector with its direction to the incoming flow that was the motivation for carrying out this work.

DESCRIPTION OF MODEL EXPERIMENTS AND ANALYSIS

Model Hull and Propulsion System

The tug in question was designed by Robert Allan Ltd. and was fitted with twin vertical axis (VSP) propellers designed by Voith-Hydro GmbH. A detailed description of the tug is given in another paper (Allan et al, 2000). The model, built by IMD to a scale of 1:18, was fitted with a skeg and a protective cage for the VSP units. A photograph of the model is shown in Figure 1. The general particulars of the tug are given in Table 1. An oversize bulwark was fitted to prevent the model from flooding at large heel angles.

Length, w. l., m	38.2
Beam, w.l., m	14.2
Draft, maximum, m	3.8

Table 1, Summary of Tug Dimensions

The model, including propulsion motors and instrumentation was ballasted to obtain the correct value of transverse metacentric height (GM).

Vertical axis propellers consist of several high aspect ratio foils, normal to the hull. Each blade moves in a circular orbit about the centerline of the propeller. Varying the angle of attack of each blade as it moves around the orbit generates a net propulsive force. For VSP propellers, each blade makes one complete rotation about its own axis in the course of its orbit, so that the same edge is leading throughout. As a result, an airfoil section can be used. The magnitude of the thrust can be controlled by varying the maximum angle of attack of each foil, or by increasing the rate of rotation for the propeller. Changing the point on the orbit at which the maximum angle of attack occurs varies the direction of the force. In normal operation the rate of rotation is kept constant, and the vessel is propelled and steered by using a control system that adjusts angle of attack and force direction. When two propellers are fitted in parallel, a single control system is used and each propeller is set to the same control position. The resulting system gives a ship exceptional maneuverability due to the ability to vary thruster force and direction almost instantaneously.

Models of twin VSP propulsion units were provide by Voith Hydro GmbH. The propellers were fitted to the model, so that the port propeller turned counterclockwise and the starboard propeller turned clockwise, when viewed from above. A summary of the geometry of the model propellers is given in Table 2. A photograph of the propellers fitted to the tug is given in Figure 2.

Figure 1, Tug model prior to testing, hull only.

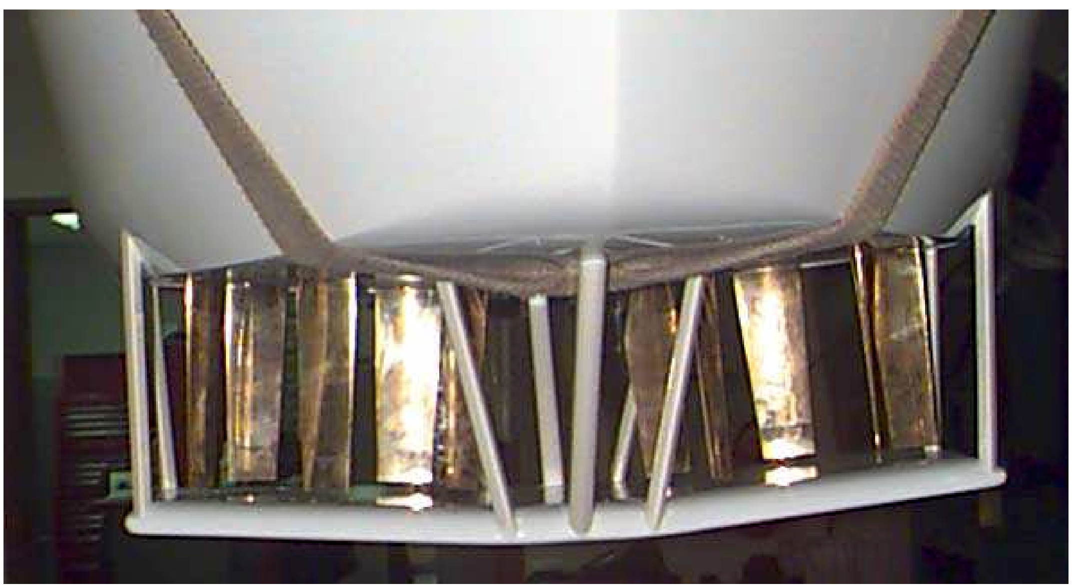

Figure 2, VSP units fitted to hull.

Propeller diameter, mm	200
Propeller blade span, mm	150
Blade chord length at root, mm	53.75
Blades per propeller	5
Distance between propeller centers, mm	338

Table 2, Summary of Propeller Particulars

The model propellers did not function in exactly the same manner as the prototypes. The models used cams to rotate the blades, rather than linkages, which are used on the prototype. The advantage is a robust model, but the disadvantages are that the maximum angle of attack and its location in the propeller blade orbit are fixed. Direction of the propulsion system force was varied by manually rotating the propulsion system within the model. Each propeller was set to the same nominal angle, using a graduated scale on the propellers' seats. For the model experiments, thrust was varied by changing the rate of rotation, with each propeller turning at the same rate. Experiments were only carried out with one set of cams, which corresponded to 100% angle of attack. The model propellers also included a 2:1 reduction gear between the motor and the propeller.

Prior to the propulsion experiments, the relationship between control voltage, torque and rate of rotation for each motor was derived. A test rig was built for this purpose, with a drive motor, a brake motor and a torque dynamometer connecting the two together. This was necessary, since the model propellers were not instrumented to measure torque. Prior to each day's testing, the friction of each VSP unit was measured in air. For this data, the model propellers were run over the range of operating rotation rates and the torque in air measured. The difference between the total torque in water and the total torque in air, at the same rate of rotation was used to obtain the hydrodynamic torque during an experiment. Thrust generated by the propellers was not measured.

Model Experiments

The first phase of the experiment program was to obtain hydrodynamic forces for the hull and appendages alone. The propellers were removed for these experiments and replaced with watertight plugs, fitted flush with the hull surface. The test methodology was adapted from the method described by Hutchison (1993). IMD's Planar Motion Mechanism (Spencer and Williams, 1998) was used to obtain hydrodynamic forces and moments. The model was fixed at a given yaw angle and measurements were made of surge and sway forces for the range of operating speeds and yaw angles. The load measurement system was connected to the tug on an axis along the centreline, at the height of the towing staple. The model was free to roll about the axis through the towing staple, and free to pitch and heave. The most important variables measured were sway force (forward and aft) and surge force. Yaw moment was calculated from the difference between the forward and aft sway force measurements, and total sway force was the sum of the two measured sway loads. Pitch angle, roll angle, heave amplitude and carriage speed were also measured. A tug-based coordinate system was used for measured forces and moments. The test matrix used to collect data for the hull alone is given in Table 3.

The same partially captive system was used for measuring the forces created by the combination of the hull and the operating propulsion system. In addition to the parameters measured for the experiments on the hull only, the propulsion system performance of the model was measured. The VSP models were marked with the point at which the maximum angle of attack occurred. The angle between this mark and the centerline of the tug was called the thruster angle. Thruster angles were set to cover the expected range required for direct and indirect modes of operation. For each tug speed and yaw angle a range of thruster angles and shaft rotation rates were tested, to bracket zero yaw moment about the towing staple. Rates of rotation were varied with thruster orientation to keep the maximum power absorbed by the propellers close to the maximum power available for the ship. The test matrix for the combined hull and propulsion system is show in Table 4. Figure 3 shows the model being tested on the PMM.

In order to estimate the force due to the propulsion system, it was necessary to combine the data from the two sets of tests. Data for the hull and propulsion system was sorted for constant speed and yaw angle to match the same speeds and yaw angles used in the hull only data. Corrections to the hull only data were obtained by cross-plotting the data, since there were sometimes small differences in yaw angle between the two data sets. Surge, forward sway and aft sway forces for the hull alone were subtracted from the combined hull and propulsion data to give an estimate of the forces due to the propulsion system. This gave the set of variables described in Table 5.

These however are not necessarily the most useful variables for analyzing the performance of the propulsion system. Total or resultant force can be calculated from the forward sway, aft sway and surge forces. The angle of this force, γ, is referred to in this paper as the dynamic thrust angle, and is the angle created by the surge and sway forces relative to the centerline of the tug, estimated for the propeller alone. In some cases (such as the zero speed, propulsion and crash stop conditions) the thruster angle, δ, and the dynamic thrust angle, γ, will be the same, but as the tug is towed forwards, at non-zero yaw angles, there is a tendency for the incoming flow to interact with the propulsion system and the two angles are no longer coincident.

Since the propellers extend beyond the keel of the ship, we can speculate that they are largely unaffected by the wake of the hull. As a result, another angle relevant to the hydrodynamics is likely to be the inflow angle, which is the angle between the direction of motion (along the centerline of the tank) and the direction of the thruster. This was calculated as β-δ. This term, ι, is referred to as the static inflow angle, since it was based on the thruster angle set. These components are shown pictorially in Figure 4.

model speed m/s	yaw angle degrees												
	0	10	15	20	25	30	35	40	45	60	75	90	105
0.485	*	*	*	*	*	*	*	*	*	*	*	*	*
0.728	*	*	*	*	*	*	*	*	*	*	*	*	*
0.971	*	*	*	*	*	*	*	*	*				
1.213	*	*	*	*	*	*	*	*	*				
1.456	*	*	*	*	*	*	*	*	*				

Table 3, Test Matrix for Hull Only

Thruster angle, degrees	Yaw angle, degrees														
	0	5	10	15	20	25	30	35	40	45	50	55	60	75	90
0	*, ^	*	*	*	*,^	*,^	*,^	*,^	*	*					
5		*	*												
10		*	*	*	*										
15		*		*	^	*		*							
20			*		*,^	^	*,^		*						
25				*		*,^	^	*,^							
30					*		*,^	^	*,^						
35						*		*,^	^						
40							*		*,^						
105											%	%	^	^	^
120										^,%	%	%	^	^	^
135								%		^,%	%	%	^	^	^
150				^	%		^,%	%		^,%					
165				^	%		^,%	%							
180	^,%			^	%		^,%	%		^,%	%	%	^	^	^

Legend

V m/s	N rps			
	2.3	3.05	3.8	4.55
0.485		^	^	^
0.728		^	^	^
0.971	%	*,%	*,%	*
1.213	%	*,%	*,%	*
1.456	%	*,%	*,%	*

Table 4, Test Matrix for combined hull and propulsion system

Figure 3, Tug model on planar motion mechanism

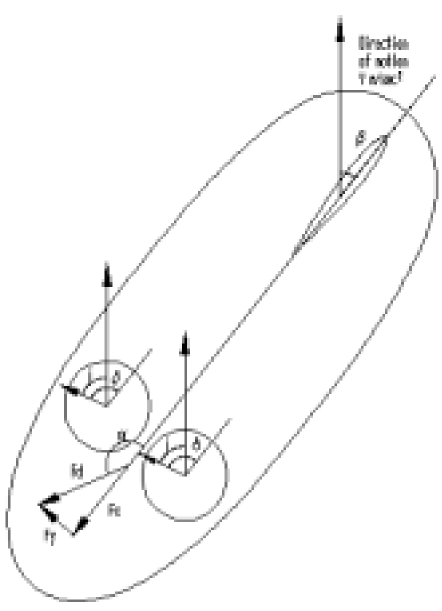

Figure 4, Force components and angles

Carriage speed, m/s
Yaw angle, β, relative to centreline of tank, degrees
Thruster angle, δ, relative to centreline of tank, degrees
Surge force, N
Forward sway force, N
Aft sway force, N
Propeller rotation, 1/sec
Port propeller hydrodynamic torque, N-m
Starboard propeller hydrodynamic torque, N-m

Table 5, Basic variables, propulsion system alone

Another parameter that was calculated was the ratio of the port torque to the total torque. This parameter was used to indicate the level of asymmetry in the forces developed by the propulsion system. For the yaw angles used in the test matrix, the port propeller was always in an upstream position relative to the starboard one.

The ideal presentation of this data would be a set of non-dimensional coefficients for propeller force as a function of input parameters, such as ship speed, thruster angle, and rate of propeller rotation. The presentation should also match with known performance analysis methods, and allow us to study the performance of the propeller, separately from the performance of the hull. The most logical set of coefficients would be thrust and torque coefficients presented as functions of advance coefficient, as used in open water analysis. There is the need for a parameter that accounts for the variation of these forces as the angle between the position of the propeller's maximum angle of attack and the direction of the incoming flow is changed. Several parameters were investigated but the most useful was found to be inflow angle, which intuitively related to the hydrodynamics, and was easily calculated from the yaw angle and the set thruster angle.

Two additional parameters are required to fully define the performance of the propulsion system. One is the angle of the force relative to a reference system, preferably within the tug. This was the dynamic thrust angle, γ, discussed above. The other is the distribution of the propeller forces between the port and starboard propellers, and this was the ratio Qp/Q_{total}.

Unfortunately not all these coefficients could be obtained from the experiments. The nature of the propeller model did not allow the separate measurement of thrust. The next most logical variable to use was a 'tow force' coefficient, based on the calculated propulsion force discussed above. IMD's standard tow force coefficient, Kfd, is a non-dimensional coefficient in the same form as thrust coefficient, but it represents the total force generated by the combined propellers. Since the flow conditions are not necessarily symmetric, the force per propeller cannot be determined. This force coefficient also includes any interaction effects between the hull, the protective cage and the propeller. Given that total tow force is available, total torque is the other logical propeller performance coefficient. Advance coefficient was calculated from the data, based on the speed of the model, rather than the speed of the flow.

DISCUSSION OF RESULTS

The nature of the test matrix, with constant speeds and propeller shaft rotations, resulted in there being large amounts of data at relatively constant values of advance coefficient over a range of inflow angles, from 40 to -180 degrees. Also, since the variation in the magnitude of the propulsion force with thruster angle was the primary interest, the final data presentation methods selected were Kfd , Kq_{total} and Qp/Q_{total} as functions of static inflow angle, for contours of constant advance coefficient. Four advance coefficient values were picked for this paper, to illustrate the change in each variable over most of the range of operating speed of the tug during escort maneuvers and over the full range of inflow angles. Polynomial coefficients were fitted to these data and the resulting equations were either third or fourth order polynomials. The equations are based on inflow angle in radians, since the magnitude of the coefficients in this form covered three orders of magnitude, whereas when degrees was used, the range of the coefficients increased significantly.

Figure 5 shows Kfd against static inflow angle, ι, for advance coefficient, J, values of 0.00, 0.55, 1.00 and 1.60. This figure clearly shows the variation in propulsion system force as the advance coefficient and inflow angle are changed. At zero inflow angle the data follow the expected trends of a propeller open water curve with Kfd decreasing with increasing advance coefficient. However as the magnitude of the inflow angle is increased, the magnitude of Kfd increases with increase in advance coefficient, which is the opposite of what would normally be expected from a propeller generating thrust. Maximum Kfd is obtained for the highest value of J at inflow angles of approximately 90 degrees. Beyond an inflow angle of 90 degrees, the force decreases until at 180 degrees inflow angle, the force is slightly higher than the value at zero degrees.

The maximum force occurs when the propeller is thrusting across the incoming flow, at the maximum speed of advance for the propeller. We speculate that it is the creation of an accelerated region of flow normal to the incoming flow that is causing this large increase in total force. The magnitude of the maximum force is approximately twice the value of the force at zero advance coefficient. The maximum force is not thrust in the conventional sense, since it is directed normal to the direction of motion. For escort tugs assisting the tanker at high speed, maximum force is more important than maximum thrust, since this is an overload situation, with the tug being pulled by the tanker.

The variation of Kfd with inflow angle at zero advance coefficient should be discussed. In this case, it is reasonable to expect that this value should be constant over the full range of inflow angles, provided that there was no interference between the two propellers, when the wake of the upstream propeller interacts with the downstream propeller. Based on the geometry of the combined propellers, interference can be expected for thruster angles between –60 and –120 degrees. Any data points in this range were removed from the regression analysis. Since these data points were eliminated, the effects of interference between the propellers should have been removed. However, we can observe the flow into the propellers is not symmetric fore and aft, due to the combination of the hull shape and the base of the propeller protection cage. In this case, the protective cage is acting like a propeller duct, and creating more force in one direction than the other.

Based on the data given in Figure 5, it is a reasonable assumption that the force generated by the thruster is constant for zero advance coefficient, provided that there was no influence of the hull and the propeller cage. Also it would be reasonable to assume that the propulsion system force was constant over a small range of inflow angles, either side of the zero inflow angle condition. This corresponds to the maximum steering force conditions, which is usually the most critical feature of escort tug performance specification.

At inflow angles of 180 degrees, there is very little variation in Kfd with J. This is the crash stop situation, where the propellers are thrusting astern, but are being pulled forwards by the tanker.

Figure 6 shows Kq_{total} against static inflow angle, ι, for the same values of advance coefficient. These data show similar trends to the Kfd data, for advance coefficients up to 1.00, but for the highest advance coefficient value, the shape becomes more complex and for inflow angles over 70 degrees, Kq_{total} values start to decrease, until at inflow angles larger than 120 degrees, Kq_{total} values are the lowest. The variation in magnitude of Kq_{total} with advance coefficient is much smaller than the variation in Kfd. This shows that the relationship between Kfd and Kq_{total} when the inflow angle becomes significant is not the same as the relationship at small inflow angles, where it is more typical of pure propulsion conditions. At zero inflow angle, the propulsion system performance has a maximum efficiency of approximately 45%, which is close to data available from other vertical axis propellers.

Figure 7 shows the degree of asymmetry in the torque distribution. For zero advance coefficient, a polynomial has been fitted based on least squares deviation from the line, however, the scatter within the data is such that a constant value of even distribution between the two propellers is within the scatter of the data. However, as the advance coefficient increases the level of asymmetry increases, so that at 90 degree inflow angles, the port propeller, which is the up-stream propeller, is absorbing approximately 65% of the total torque. This data shows the least dependency on advance coefficient.

It would be expected that at inflow angles of zero and 180 degrees there should be an even distribution of torque between the propellers, since the flow conditions are symmetrical. It can be seen that there is a slight bias at zero degree inflow for values slightly higher than 0.5, but that at 180 degrees the assumption is within the scatter of the experiment data. The difference between the results and the expectation may be due to a combination of errors or lack of precision in the calibration process to convert controller voltage to torque. The experiments were carried out over several weeks and the calibration process depends to some extent on the condition of the motor brushes. There was also the possibility of misalignment between the propellers. Propeller direction had to be set manually, and there was no transducer to measure the angle. As a result the thruster angles were recorded manually based on the scales inscribed on the models. Also note that for regular propulsion tests, the VSP units would be angled at a value other than zero, to allow for the relative velocity induced by the forward speed of the ship.

The dynamic thrust angle (direction of the resultant force) is also an important performance parameter. The propulsion system force aligns with the thruster angle at zero speed, but as the tug speed increases, then the flow from the propellers will interact with the incoming flow, and the thruster angle and dynamic thrust angle will no longer coincide. During the analysis it was found that trends in the data were consistent within two bands, but the degree of consistency between them was limited. The two sets can be described as the steering force condition, with low thruster angles and the braking force condition, with high thruster angles. Within these smaller sets, at values of constant J, there remain strong linear trends, but it was no longer on a one to one correlation as it was with the bollard.

It was also interesting to note that the test matrix resulted in a wide range of dynamic thruster and inflow angles for thruster angles of zero. This was the result of including a limiting condition, where the minimum side force was generated by the propulsion system. In many cases, the resulting inflow angle was very much different from anything that would be seen in practice. As a result of the inability to interpret this data in a meaningful way, and its lack of usefulness in practical operating situations, only data for non-zero thruster angles was considered in the final analysis.

The prediction of the direction of the propeller force was different from the other variables. Various methods were tried, and in the end step-wise multiple linear regression was found to be the best. The data was considered as two sets, based on low thruster angles ($0>\delta>-60$) and high thruster angles ($-120>\delta>=-180$). It was found during this analysis that model speed, thruster angle, yaw angle and rate of rotation were all statistically significant as predictors. It was also found that treating each predictor separately also gave a better set of predictors than using combined variables, such as J and static inflow angle. This may be due to the fact that the propellers were fitted inside the protective cages and the alignment of the propellers within the cage had an effect with speed.

Since all the variables were found to be significant, speed and rotation were non-dimensionalized as separate variables, using Froude numbers, based on the model speed and the waterline length and another based cross flow speed of the propeller blade and its diameter.

Summaries of the predictor equations are given in Table 6 for Kfd, Kq_{total} and Qp/Qt and Table 7 for γ.

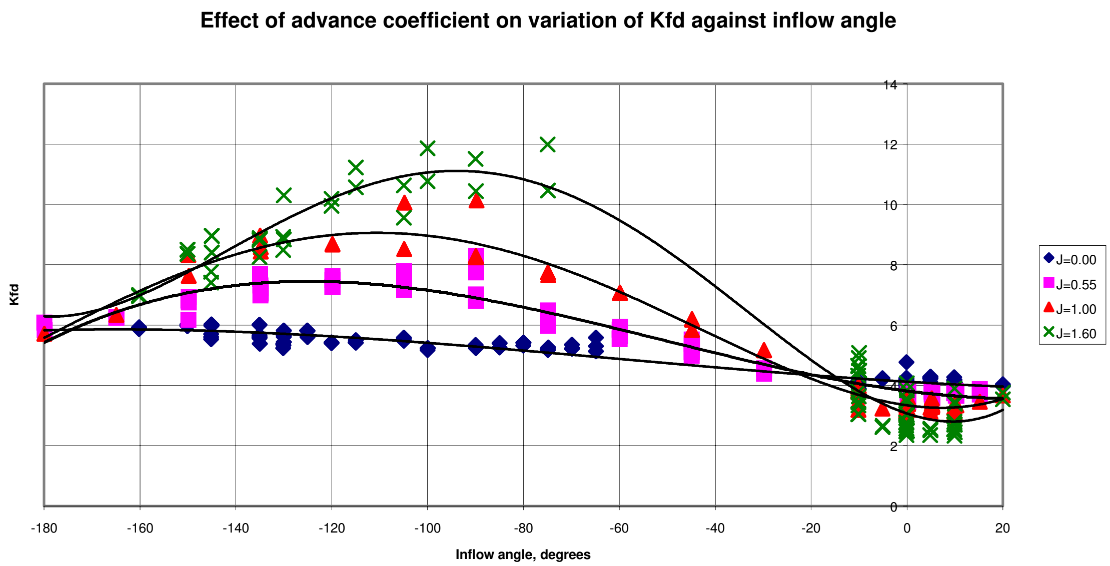

Figure 5, Kfd against inflow angle, for advance coefficients of 0.00, 0.55, 1.00 and 1.60

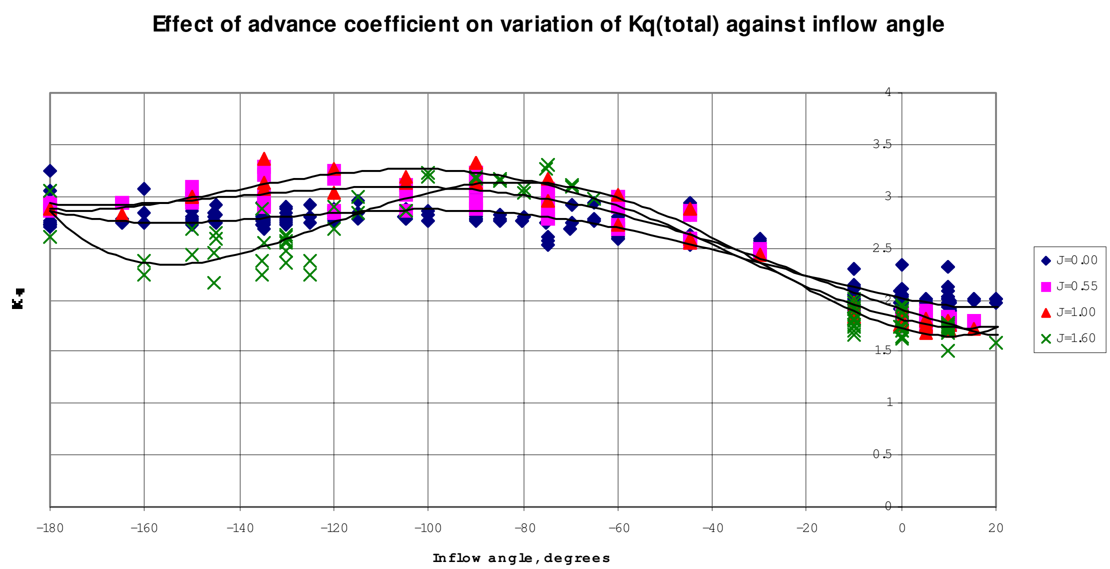

Figure 6, Kq_{total} against inflow angle, for advance coefficients of 0.00, 0.55, 1.00 and 1.60

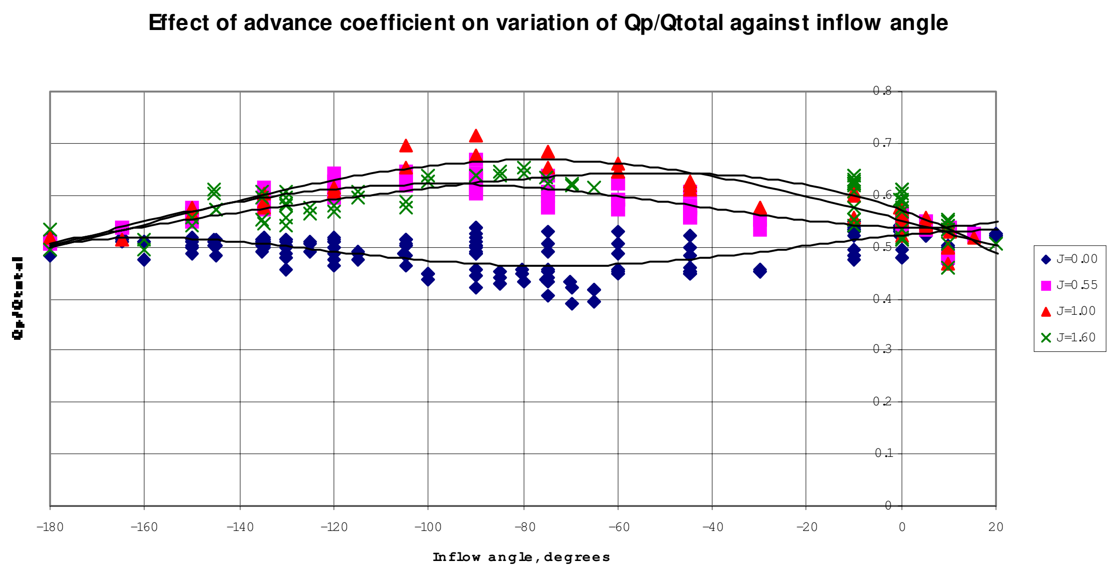

Figure 7, Qp/Qtotal against inflow angle, for advance coefficients of 0.00, 0.55, 1.00 and 1.60

J = 0	constant	inflow angle	inflow angle^2	inflow angle^3	inflow angle^4
Kfd	4.122	-0.553	0.242	0.078	0
Kq_total	2.017	-0.500	0.507	0.430	0.078
Qp/Qt	0.522	0.050	-0.048	-0.053	-0.011
J = 0.55	constant	inflow angle	inflow angle^2	inflow angle^3	inflow angle^4
Kfd	3.816	-1.185	1.208	0.453	0
Kq_total	1.907	-0.871	0.306	0.348	0.062
Qp/Qt	0.538	-0.013	0.089	0.051	0.006
J = 1.0	constant	inflow angle	inflow angle^2	inflow angle^3	inflow angle^4
Kfd	3.341	-1.261	4.461	2.458	0.313
Kq_total	1.812	-0.641	1.016	0.727	0.119
Qp/Qt	0.551	-0.14	-0.004	0.036	0.007
J = 1.6	constant	inflow angle	inflow angle^2	inflow angle^3	inflow angle^4
Kfd	3.069	-3.033	7.669	5.441	0.890
Kq_total	1.716	-0.74	1.587	1.354	0.258
Qp/Qt	0.569	-0.196	-0.163	-0.047	-0.005

Table 6, Summary of Predictor Equations for
kfd, Kq (total) and Op/Qtotal (inflow angle in radians)

Variable	units	Coefficient
Fn_length	nd	-78.157
Fn_rotation	nd	4.959
delta	degrees	2.585
beta	degrees	1.26
R^2		0.905

low delta angles (0>delta>-60)

Variable	units	Coefficient
Fn_length	nd	43.457
Fn_rotation	nd	-11.167
delta	degrees	0.809
beta	degrees	-0.399
R^2		0.995

high delta angles (-120>delta>=-180)

Table 7, Summary of Predictor Equations
for direction of resultant force, degrees

The predictor equations are simplifications of the situation, and are limited as a result. For example, heel was not included in the analysis. Heel is dependent on vessel conditions such as metacentric height, hull shape, towline force, power level, thruster angle, yaw angle and speed. It was felt that the data was not precise enough to extract reliable trends for this variable. Another omission in the method is the reaction between the protective cage and the propellers. Since both yaw angle and thruster angle combine to give the static inflow angle, different combinations of input will give the same value of output. However, since the cage is moving with the yaw angle of the tug, the struts are in different relative positions for the same value of inflow angle. This may be one reason for some of the scatter within the data.

For the experiments described in this paper, J variation was obtained by speed and rotation variation. In real operating situation, pitch is the variable that controls force and rotation is held constant. This would mean J variation would come from speed variation alone and an extra variable would be pitch variation. Open water data for vertical axis propellers suggests an approximately linear relationship between pitch and thrust and torque, for zero inflow angle. The first level of approximation would be to reduce force linearly with pitch, but this should be validated with experiments, especially at high inflow angles.

Clearly the experiment procedure described in this report is limited. A better procedure would have been to carry out open water experiments over full range of inflow angles, with measurements of thrust, rather than indirect calculation of tow force. Also the embedded effects of heel and the protective cage should have been eliminated. This in turn would have allowed hull factors to be calculated. A special propeller open water boat would be required for this. It should have the capability to handle single and twin propulsion systems, so that the interference between the two propellers can be studied in more detail.

CONCLUSIONS

The results given in this paper show that it is possible to increase the force generated by a vertical axis propeller to more than twice the force generated at the bollard condition. It is important to recognize that this force is not thrust in the classical sense, since the thruster is oriented normal to the incoming flow. However, in the case of an escort tug, maximum force generated by the propulsion system, can be used to brake the tanker it is assisting. The other interesting hydrodynamic feature about this result is that to increase the force by 100% above the bollard condition only requires a 12.5% increase in torque. At the maximum force condition, the torque distribution between the two propellers is not symmetrical, with the up stream propeller absorbing approximately 65% of the total torque.

The predictions of the performance of the propellers were limited by the nature of the experiment. Since thrust of each propeller was not measured directly, it had to be estimated from the combined results of the forces generated by the hull and the forces generated by the hull and the propulsion system. As a result, the predictions inherently include the effects of heel and interference between the propellers, the hull and the protective cage. However, since these features are common to all escort tugs using VSP systems, the limitations do not prevent the use of the predicted forces and angles in simulations of tug performance.

The experiment method can be improved to carry out open water experiments on the propulsion system alone, measuring thrust and torque, over a full range of inflow angles and advance coefficients. Despite the limitations of the experiment method, the results give important information of the variation in propulsive system forces in operating conditions that are not normally studied.

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