First International Symposium on Marine Propulsors
smp'09, Trondheim, Norway, June 2009

Experimental Testing of an Autonomous Underwater Vehicle with Tunnel Thrusters

Alistair Palmer[1], Grant E. Hearn[1], Peter Stevenson[2]

[1]School of Engineering Sciences, University of Southampton, Southampton, UK
[2]Underwater Systems Laboratory, National Oceanography Centre, Southampton, UK

ABSTRACT

Autonomous Underwater Vehicles (AUVs) are a rapidly developing technology. This development includes the creation of multi-purpose vehicles capable of combining efficient long range survey missions with low and zero speed interaction with the environment discovered. Current survey-style AUVs employ control surfaces for manoeuvring control at speed. The ineffectiveness of these control surfaces at low and zero speeds means that additional control devices are required.

In this paper the through-body tunnel thruster is considered as the additional control device. Existing published information about these thrusters is reviewed and a new experimental programme is undertaken. This experimental programme is designed to characterise the performance of both forward and aft mounted tunnel thrusters in a torpedo-shaped AUV hull form at model scale.

The results of the experimental programme are presented to show the variations in the force and moment induced on an AUV as a function of the operational conditions. Finally these results are used to develop a simple and easily applicable modelling procedure to aid in the design of AUV control systems and for use in AUV performance analysis.

Keywords

Autonomous Underwater Vehicle, Modelling, Tunnel Thruster, Experimental Techniques.

1 INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are a class of underwater vehicles which operate independently of any human control. These vehicles are controlled by onboard control systems which use the information recorded by sensors to determine the demands to be sent to the actuators. The complexity of these control systems is a function of the sensors and actuators employed and the desired vehicle performance. Another feature of the independence of AUVs is the limitation imposed by the finite energy supply which can be carried onboard. This means that design choices are heavily influenced by the associated energy cost.

There are many different types of AUV currently in use and most of these vehicles are designed for a specific purpose. Example applications of AUVs include oceanographic surveying, mine-sweeping and pipeline inspection. These widely differing applications give rise to a large number of different vehicle shapes and sizes, sensor packages and actuator configurations. As the performance of these vehicles improves, so the desire increases to use these vehicles in a larger number of scenarios. Therefore, the next stage in the development of AUVs is the creation of a multi-purpose vehicle capable of combining long range survey missions with low speed interaction and investigation style tasks.

1.1 Survey-Style AUVs

One of the first types of AUV developed was the survey vehicle. Survey vehicles undertake long range missions to investigate an area of the ocean and tend to carry sensor packages to facilitate scientific research.

A key performance indicator for a survey vehicle is the range it can achieve. This parameter allows an assessment of the design of the vehicle incorporating the propulsive efficiency and the energy storage capacity. Therefore the design of survey vehicles focuses on combining a hydrodynamically shaped hull form and a high efficiency propulsion system with the ability to carry sufficient energy alongside the mission dependent payload. This design process has resulted in a common survey vehicle design comprising a torpedo-shaped (or similar) hull form with a stern mounted propeller and control surfaces to provide control at speed.

Survey vehicles tend to be ballasted to be positively buoyant to ensure that the vehicle rises to the relative safety of the surface should the propulsion systems fail. To overcome the positive buoyancy at survey speeds, the vehicle operates at a small (nose-down) pitch angle, controlled by the hydroplanes, to generate a downwards force hydrodynamically.

As a survey vehicle slows down a speed limit is reached beyond which the control surfaces can no longer provide sufficient force to maintain the pitch angle required to control the positive buoyancy. At even lower speeds the control surfaces become ineffective and cannot provide sufficient forces to manoeuvre the vehicle in the desired manner. Thus the creation of a multi-purpose vehicle requires additional control devices to provide low speed buoyancy and manoeuvring control. The majority of underwater vehicles use propeller based thrusters to provide low speed control due to their reliability, responsiveness and ability to generate forces throughout the speed range. To attempt to retain the survey efficiency of the vehicle these thrusters can be mounted in through-body tunnels. An example thruster configuration for a multi-purpose vehicle is shown in Figure 1.

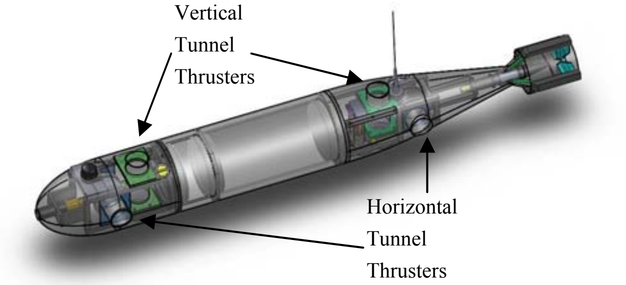

Figure 1 – Example multi-purpose AUV based on a survey-style configuration with four additional tunnel thrusters

The vehicle shown in Figure 1 has a stern mounted propeller with control surfaces attached to the duct in the propeller race. In addition the vehicle has four tunnel thrusters, two in the vertical plane and two in the horizontal plane. These additional thrusters provide control over sway, heave, pitch and yaw motions.

The vehicle shown in Figure 1 will need to use the tunnel thrusters for two key tasks. These tasks are low and zero speed manoeuvring control and the control of the positive buoyancy at speeds below the limit of control surface control. This provides two different operational envelopes for the tunnel thrusters, namely, low and zero speed operation at a wide range of vehicle orientations and at higher speeds with a limited range of pitch angle. The exact limits of these ranges are a function of the design of the particular vehicle and control surfaces.

In this paper the focus is on the latter operational envelope, that is, the performance of a tunnel thruster on a vehicle moving with a forward speed. For simplicity the analysis is restricted to zero angle of attack (pitch or yaw angle, by symmetry). Initially, it is assumed that the performance of the thruster will be consistent over the range of small angles of attack experienced at speed. This is a subject for future investigation.

2 TUNNEL THRUSTER PERFORMANCE

Simple design calculations for an AUV tunnel thruster dictate that the diameter, D, of the required thruster is small in relation to the length of the tunnel, L. The length to diameter ratio for the tunnel thruster is therefore large, for example, $L/D \sim 4$. The scale of these thrusters and their large length to diameter ratio means that they are unlike most marine thrusters and thus experiments have been undertaken to characterise their performance.

2.1 Tunnel Thruster Performance at Zero Speed

The performance of small diameter tunnel thrusters has been investigated under static conditions in McLean (1991) and Cody (1992) (D = 7.5cm; L/D = 3.5 and 5.5). These experimental results were used to develop a model of the dynamic performance of the thruster (Healey et al 1995). Here dynamic refers to the performance response of the thruster subject to a varying input signal. These experiments demonstrate the steady state performance of these devices to be similar to other propeller based thrusters, that is, the thrust generated is proportional to the square of the rotational speed. The influence of the long tunnel is seen in the dynamic performance of the thruster which is affected by the relatively large body of water within the tunnel.

2.2 Tunnel Thruster Performance on a Moving Vehicle

The performance of tunnel thrusters in a full scale AUV was investigated experimentally in Saunders & Nahon (2002). The test matrix included the full range of operational vehicle speeds (up to 4m.s^{-1}) and yaw angles up to ±90º. However, for these experiments the thruster was isolated from the hull form and the forces recorded were those generated by the thruster and not those experienced by the vehicle. The results showed a variation in thrust of around 15% over the range of forward speeds tested at zero yaw.

A further set of experimental results giving the performance of a tunnel thruster on a 'submersible', in terms of the forces experienced by the vehicle, is shown in Figure 2 (Beveridge 1972).

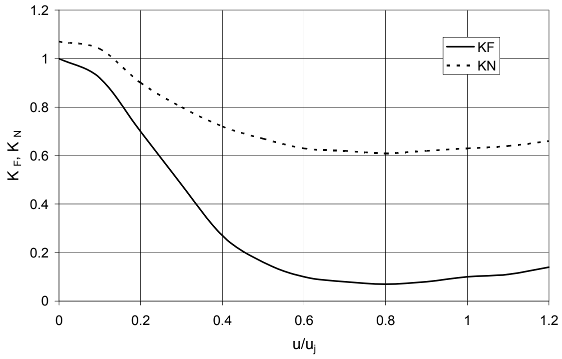

Figure 2 – Force and moment data for a tunnel thruster on a 'submersible' (Beveridge 1972)

Figure 2 uses the following coefficients to represent the performance of the thruster, see Equation 1. A force coefficient, K_F, gives the ratio of the force experienced by the vehicle to the corresponding zero speed thruster force. A moment coefficient, K_N, gives the ratio of the moment experienced by the vehicle to the corresponding zero speed moment. These coefficients are plotted against the speed ratio of the vehicle forward speed, u, to the thruster jet exit speed, u_j.

$$K_F = \frac{F_T(u,n)}{F_T(0,n)} \tag{1a}$$

$$K_N = \frac{N_T(u,n)}{N_T(0,n)} \tag{1b}$$

$$\frac{u}{u_j} = \frac{u}{\sqrt{\frac{F_T(0,n)}{\rho A}}} \tag{1c}$$

Here F_T is the force on the vehicle caused by the thruster, N_T is the moment on the vehicle induced by the thruster, n is the rotational speed of the thruster, ρ is the density of water and A is the cross sectional area of the thruster.

The data shown in Figure 2 shows a variation in force of up to 93%, which is considerably more than that recorded in Saunders & Nahon (2002). This indicates that the variation in force is not solely due to a change in the performance of the thruster unit itself.

2.3 Lateral Thrusters on Surface Vessels

The performance of a tunnel thruster on an underwater vehicle is analogous to the performance of a lateral thruster on a surface vessel. The performance of lateral thrusters has been investigated by, amongst others, Nienhuis (1992), English (1972), Brix & Bussemaker (1973) and Chislett & Björheden (1966). This research includes measurements of the forces and moments on various vessel types, simple flow visualisation experiments and pressure measurements around the thruster tunnel.

The experimental results for a lateral thruster on a model tanker from Chislett & Björheden (1966) are shown in Figure 3. These results show similar trends to the submersible data in Figure 2, including a large decrease in effective force with increasing speed ratio. However, there are differences including a substantial recovery of the effective moment at higher speed ratios and a higher minimum effective force.

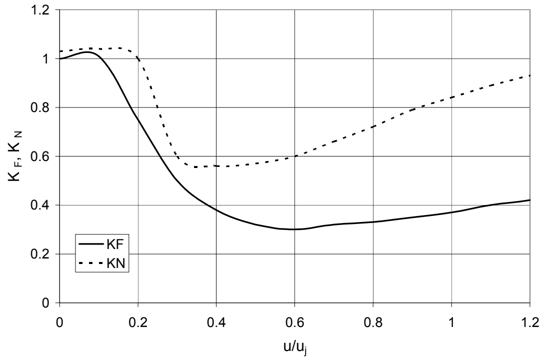

Figure 3 – Force and moment data for a lateral thruster on a tanker (Chislett & Björheden 1966)

The surface vessel results, and the conclusions drawn, provide an insight into the reasons behind the variation in the performance of a lateral thruster. The thruster itself can be considered as a jet producing device. Hence when the vessel is stationary the jet flows away from the vehicle, see Figure 4 (dashed lines represent the path of the jet). However when the vehicle is moving forwards the thruster jet is deflected as a function of the relative strength of the jet to the strength of the ambient flow. As the thruster jet flow develops, fluid is entrained into the jet, causing a suction effect around the jet. When the jet is deflected backwards this suction region interacts with the vehicle, inducing a force on the vehicle opposite to the desired thruster force, see Figure 5 (shaded area represents the suction effect). The offset of this suction force from the thruster force causes a further variation in the moment experienced by the vehicle. (New symbols used on Figures 4 and 5 are defined later, where appropriate).

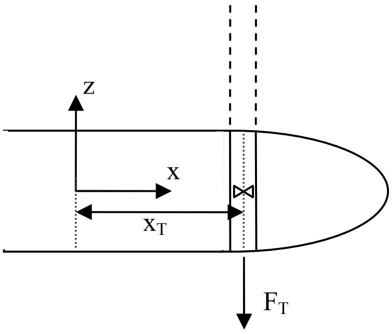

Figure 4 – Schematic of tunnel thruster performance at zero speed

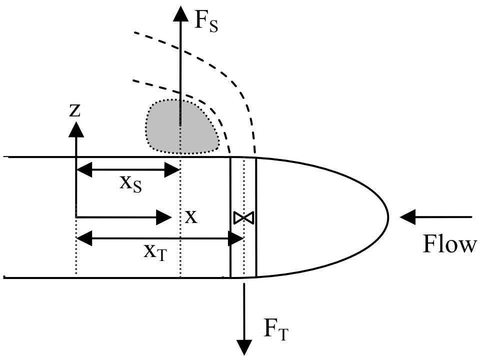

Figure 5 – Schematic of tunnel thruster performance on a vehicle moving with a forward speed

This representation of the operation of a tunnel thruster ignores the influence of suction effects upstream of the tunnel outlet and around the tunnel inlet. Pressure measurements around the inlet and outlet of the tunnel have shown that the primary cause of the loss of effective force is the influence of the suction downstream of the tunnel outlet (English 1972; Brix & Bussemaker 1973).

The complexity of the interaction between the ambient flow (including the boundary layer), thruster jet and vehicle mean that the performance of each different thruster configuration is unique. Therefore to be able to characterise the performance of a tunnel thruster on an AUV type body an experimental approach was adopted.

2.4 AUV Simulation

Simulations are commonly used in the development of AUVs to aid in control system design and to gain insight into the performance of the vehicle. For the simulations to accurately reflect the performance of the vehicle it is necessary to model the influence of the actuators employed. However, no common modelling approach for the performance of a tunnel thruster is readily available. This is thought to be due to the complexity of the interactions involved and the uniqueness of each configuration.

Published AUV simulations tend to assume that the forces experienced by the vehicle are equal to those generated by the thruster and that the induced moment can be calculated according to geometric considerations (for example, Ananthakrishnan et al (1998)). Saunders & Nahon (2002) did modify the existing Healey et al (1995) thruster model using a look-up table of experimental results. However, as the experimental results do not account for the ambient flow effects, the model does not represent the complete performance. Hence the results obtained from the experiments undertaken will be used to develop a modelling approach for the performance of a tunnel thruster on an AUV.

3 EXPERIMENTAL SETUP

A 2.5m, approximately one-third scale, model of the survey AUV Autosub 3 (Fallows 2004) was modified to accommodate two horizontal through-body tunnels, one forward and one aft, as shown in Figure 6. The tunnel locations were selected by considering the vehicle performance across the entire operating envelope and the existing use of internal space. Each tunnel has a diameter equal to that of the thruster mounted within the tunnel and the tunnels are symmetrically faired into the shape of the vehicle at the inlet and outlet. The particular thrusters used are 70mm diameter rim driven thruster units (Abu-Sharkh et al 2003). These thruster units are well suited to this application as they provide symmetrical performance and minimise the blockage in the tunnel caused by the hub. The thrusters were driven using an electronic speed controller connected to a computer. The rotational speed of the thruster was measured by monitoring the control signal using a frequency counter and the electrical power drawn was recorded.

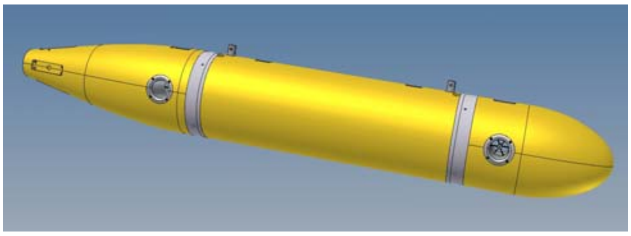

Figure 6 – CAD drawing of the Autosub model showing forward and aft thruster tunnels (control surfaces and stern propulsor not shown)

The tank used for the testing was the Southampton Solent University Towing Tank which is 60m long, 3.7m wide and 1.85m deep and has a carriage which can run up to $4.25 m.s^{-1}$. The model was mounted, via a pair of mounting poles, onto a purpose designed and built dynamometer which incorporates four force blocks (Fallows 2004). Each force block uses a linear variable differential transformer to measure the transverse displacement induced by a force applied between the top and bottom of the block. The force blocks are mounted in orthogonal pairs on each mounting post to measure drag and side force. Each force block was calibrated using a multi-point calibration using calibrated weights. The force block signals were digitised and passed to a computer for automatic data logging. The data was recorded at 60Hz.

The test programme for the experiments was designed to cover the range of operational conditions expected and was undertaken in stages. Firstly, the drag of the vehicle was measured over the full range of carriage speeds (up to $4.25 m.s^{-1}$). Following this the thruster performance was characterised at zero speed over the range of rotational speeds to be used in the testing. Finally the vehicle was run with the thrusters operating at selected rotational speeds (to give an appropriate range of speed ratio) using four different vehicle speeds – approximately $0.4 m.s^{-1}$, $0.6 m.s^{-1}$, $0.8 m.s^{-1}$ and $1.0 m.s^{-1}$. The results of these tests are detailed in the following sections.

4 RESULTS

The drag of the vehicle was recorded, without the thrusters operating, to assess the survey drag impact of adding thruster tunnels to an AUV hull form. The increase in the drag of the vehicle, with thruster tunnels compared to without thruster tunnels, at survey speeds, was less than 2%.

4.1 Thruster Performance at Zero Speed

The force generated by the thruster, F_T, at zero vehicle speed was recorded throughout the range of rotational speeds, n. These results are illustrated in Figure 7 showing a linear trend of thruster force with the square of the rotational speed as expected. Furthermore, these results closely match the data published by the manufacturer for the thruster operating with its standard duct fitted (TSL 2006).

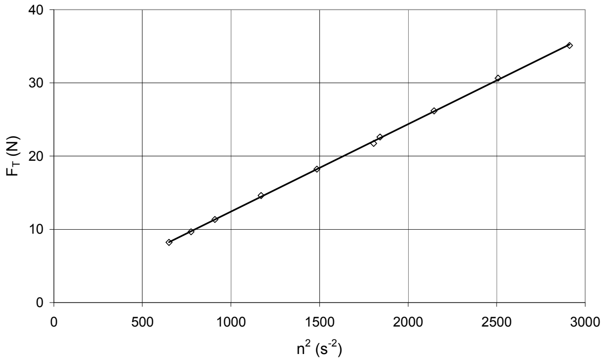

Figure 7 – Tunnel thruster performance at zero speed showing thrust, F_T, against the square of the thruster rotational speed, n^2

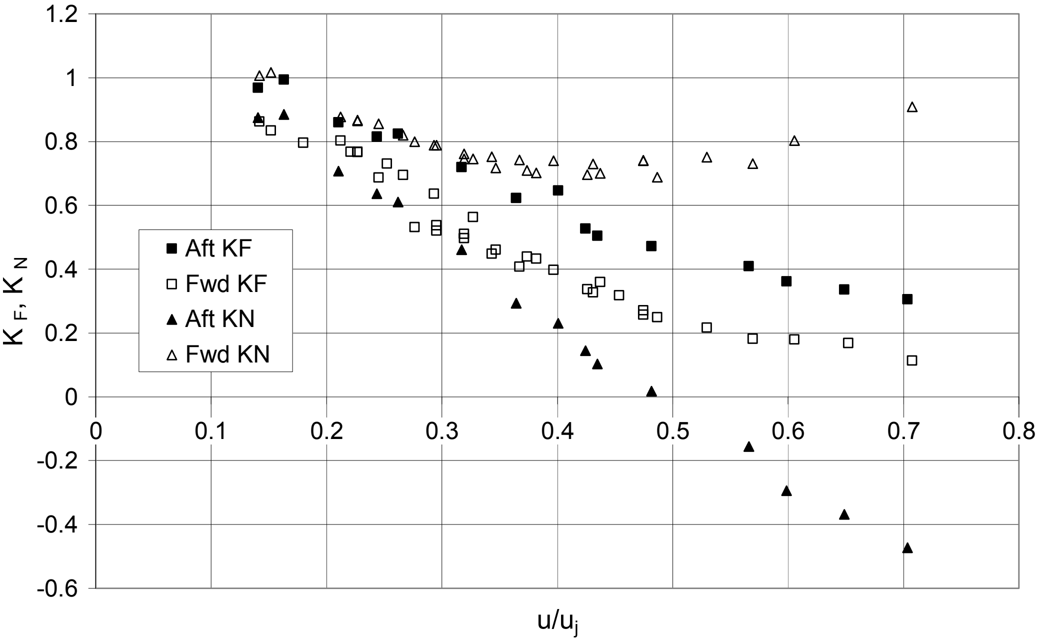

Figure 8 – Tunnel thruster performance for forward (hollow symbols) and aft (solid symbols) thrusters on an AUV moving with a forward speed

4.2 Thruster Performance on a Moving Vehicle

The results for the forward and aft thrusters across the range of speed ratio are shown in Figure 8. The data recorded is presented using the coefficients defined in Equation 1. The forces induced by the operation of the thruster are determined by calculating the difference between the forces recorded at a given speed with and without the thruster operating.

These results show a large drop off in the force experienced by the vehicle with increasing speed ratio for both the forward and aft thrusters. This data shows a similar form to that presented in Beveridge (1972) (Figure 2). The differences between the force trends for the forward and aft thrusters are an indication of the influence of the differing form of the vehicle around the two tunnel exits. The hull form aft of the rear tunnel slopes away from the tunnel whereas the hull form aft of the forward tunnel is flat. This variation will give a differing interaction between the deflected jet and the vehicle and as a consequence results in differing performance characteristics.

Figure 8 also shows that the moments induced by the thrusters drop off considerably with increasing speed ratio. However, there is a notable difference between the variations for the two thrusters. In order to gain some insight into these variations it is necessary to understand the forces acting on the vehicle. A simplified representation of a tunnel thruster uses two forces (see Figure 5). These are the thrust force generated, assumed to act at the thruster axis, and a total suction force, which acts at a variable point as a function of speed ratio.

The suction force, F_S, is defined as the difference between the expected (zero speed) force and the force experienced by the vehicle, see Equation 2. The suction moment, N_S, is defined as the difference between the expected (zero speed) moment and the moment experienced by the vehicle.

$$F_S(u,n) = F_T(0,n) - F_T(u,n) \tag{2a}$$

$$N_S(u,n) = N_T(0,n) - N_T(u,n) \tag{2b}$$

The centre of action of the suction force, x_S, is then defined as the ratio of the suction moment to the suction force:

$$x_S(u,n) = \frac{N_S(u,n)}{F_S(u,n)}. \tag{3}$$

Figures 9 and 10 show the variation of the centre of action of the suction force, with speed ratio, for the forward and aft thrusters, respectively.

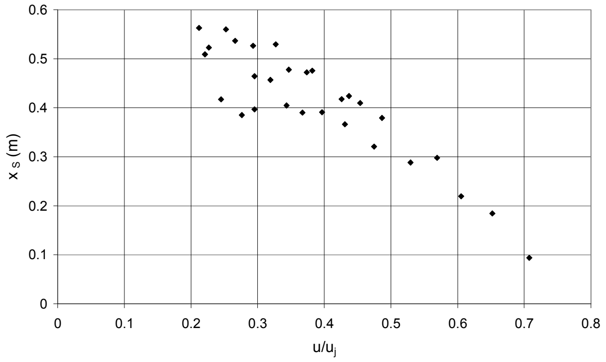

Figure 9 – Centre of action of the suction force, x_S, for the forward tunnel thruster against speed ratio, u/u_j

These results show that the centre of action of the suction force for the forward thruster moves aft (towards zero) with increasing speed ratio. This movement is towards the central pivot point of the vehicle and thus reduces the impact of the suction moment, giving the limited reduction in moment shown on Figure 8. For the aft thruster the centre of action is roughly constant and aft of the thruster, giving a relatively greater influence of the suction moment. This leads to the point at a speed ratio of approximately 0.5, where the aft thruster moment coefficient changes sign as the suction moment dominates the moment created by the thruster force. The reason behind this relatively constant centre of action for the aft thruster is thought to be due to the truncation of the hull form downstream of the tunnel exit.

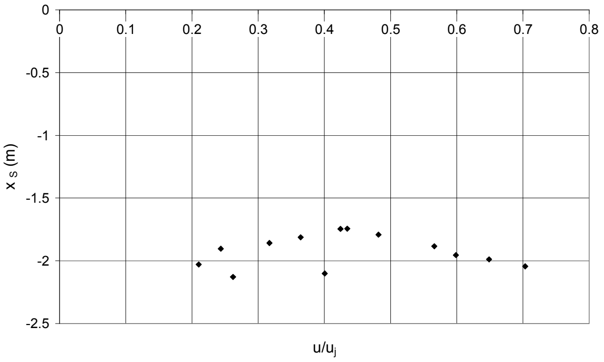

Figure 10 – Centre of action of the suction force, x_S, for the aft tunnel thruster against speed ratio, u/u_j

Both thrusters were run simultaneously, in the same and opposite directions, and no interaction effects were experienced at the large thruster separation used. Thus, the performance of the two thrusters combined is equal to the sum of the performance of the individual thrusters.

4.3 Thruster Induced Drag

The drag force on the vehicle was recorded during the thruster experiments. Figure 11 shows the increase in volumetric drag coefficient, ΔC_D, compared to the thruster-off case, against speed ratio.

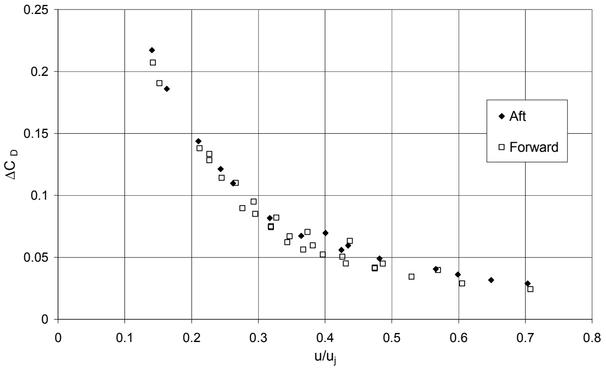

Figure 11 – Increase in volumetric drag coefficient, ΔC_D, against speed ratio, u/u_j, for the forward (hollow symbols) and aft (solid symbols) thruster operation

These results show that the increase in drag reduces as speed ratio increases and the variation is the same for both thrusters. At the low speed ratios, where the jet dominates the ambient flow and effectively forms a cylinder in the flow, the increase in drag is the largest. As the speed ratio increases, and the jet is deflected more by the ambient flow, the increase in drag reduces. Note should be made that the vehicle drag at low speeds is small and hence a large increase in drag coefficient does not correspond to a prohibitive increase in actual force.

5 TUNNEL THRUSTER MODELLING

Accurate simulation of the performance of an AUV equipped with tunnel thrusters requires a model of how the operation of these thrusters affects the vehicle. Since no established modelling procedure is readily available, the data obtained from these experiments will be used to develop a simple and easily applicable model.

Yoerger et al (1990) state that at low speeds the control of an AUV can be dominated by the dynamics of the thrusters employed. Therefore it is important to include the dynamic effects of the thruster in the modelling procedure. Saunders & Nahon (2002) concluded that the dynamic performance of the tunnel thruster tested was unchanged by the range of experimental conditions experienced. This conclusion is backed up by a series of dynamic experiments undertaken using the experimental setup tested here. Therefore, existing models of the dynamic performance can be employed, for example, Healey et al (1995).

To model the steady state performance of the thruster an exponential can be fitted to the force results of the form:

$$K_F = \exp\left[-c\left(\frac{u}{u_j}\right)^2\right]. \tag{4}$$

The force experienced by the vehicle can readily be determined by applying a model of the performance of the thruster at zero speed. The selection of the constant, c, is a function of the individual configuration tested. Using a least squares approach, $c \approx 7$ for the forward thruster and $c \approx 3$ for the aft thruster.

To model the moment experienced by the vehicle, the simplified representation consisting of only two forces is used. Thus, the moment is given by:

$$N = F_T x_T + F_S x_S . \tag{5}$$

The thruster force, F_T, is determined from a zero speed thruster performance model and the thruster moment arm, x_T, is determined using the geometry of the vehicle. The suction force, F_S, is determined from Equation 2 and the suction moment arm, x_S, is represented using a simple model. Chislett & Björheden (1966) conclude that the centre of action of the suction force moves linearly aft with increasing speed ratio. The results for the forward thruster, presented in Figure 9, show some agreement with this conclusion, giving a model of the form:

$$x_S = x_T - kD\frac{u}{u_j} . \tag{6}$$

Here k is a configuration dependent constant. However the results for the aft thruster do not follow this linear trend and hence a constant value of x_S is applied here. These results show that it is important to account for the shape (and truncation) of the body when selecting the model structure used for the suction moment arm.

6 CONCLUSIONS

To create a multi-purpose AUV capable of undertaking both survey-style missions and low speed interaction with the environment encountered requires the addition of further control devices to augment common survey AUV configurations. To retain the existing survey efficiency one available option for these additional control devices is the through-body tunnel thruster. This paper reviews the available published data for the performance of tunnel thrusters on AUV type bodies and finds a need for additional experimental testing.

Therefore experiments were undertaken using rim driven thrusters mounted in fore and aft through-body tunnels on a model scale torpedo-shaped AUV. The results of these experiments are presented to show how the forces and moments experienced by the vehicle, due to the operation of the tunnel thruster, vary as a function of the operational conditions. These results show considerable decreases in the force and moment induced on the vehicle by the thruster with increasing speed ratio. These results also show how the variations in the shape of the vehicle around the tunnels can lead to substantially differing performance.

To aid in control system design and AUV performance analysis, a simple and easily applicable modelling procedure for the performance of a tunnel thruster on an AUV type body, as determined from the experiments, has been presented.

The work reported here forms part of a wider research project investigating approaches to extending the capabilities of survey-style autonomous underwater vehicles.

ACKNOWLEDGEMENTS

The authors would like to thank TSL Technology Ltd for the loan of the rim driven thruster units used in the experiments, the technical staff in the School of Engineering Sciences at the University of Southampton for their help in setting up the experiments and the Engineering and Physical Sciences Research Council (UK) for financial support.

REFERENCES

Abu-Sharkh, S.M., Turnock, S.R. & Hughes, A.W. (2003). 'Design and Performance of an Electric Tip-Driven Thruster'. Journal of Engineering for the Maritime Environment, Proceedings of the Institution of Mechanical Engineers, **217**(M), pp. 133-147.

Ananthakrishnan, P., Vantouroux, S., Zhang, K. & Smith, S. (1998). 'Nonlinear Dynamics and Hydrodynamics Considerations in the Design of an Autonomous Underwater Vehicle'. Proceedings of Oceanology International 1998, Brighton, UK, pp. 119-128.

Beveridge, J.L. (1972). 'Design and Performance of Bow Thrusters'. Marine Technology, **9**(4), pp. 439-453.

Brix, J.E. & Bussemaker, O. (1973). 'Lateral Thrusters with Anti-Suction Tunnels'. Proceedings of the 1st North American Tug Convention, Ship & Boat International, Vancouver, Canada, pp. 263-284.

Chislett, M.S. & Björheden, O. (1966). Influence of Ship Speed on the Effectiveness of a Lateral-Thrust Unit. Report Hy-8, Hydro-og Aerodynamisk Laboratorium, Lyngby, Denmark.

Cody, S.E. (1992). Experimental Study of the Response of Small Tunnel Thrusters to Square and Triangular Wave Inputs. Masters Thesis, Naval Postgraduate School, Monterrey, CA, USA.

English, J.W. (1963). 'The Design and Performance of Lateral Thrust Units for Ships'. Transactions of RINA, **105**(3), pp. 251-279.

Fallows, C.D. (2004). Characterisation of the Propulsion Systems of Underwater Vehicles. PhD Thesis, University of Southampton, Southampton, UK.

Healey, A.J., Rock, S.M., Cody, S.E., Miles, D. & Brown, J.P. (1995). 'Toward an Improved Understanding of Thruster Dynamics for Underwater Vehicles'. IEEE Journal of Oceanic Engineering, **20**(4), pp. 354-361.

McLean, M.B. (1991). Dynamic Performance of Small Diameter Tunnel Thrusters. Masters Thesis, Naval Postgraduate School, Monterrey, CA, USA.

Nienhuis, U. (1992). Analysis of Thruster Effectivity for Dynamic Positioning and Low Speed Manoeuvring. PhD Thesis, Delft University, Delft, Netherlands.

Saunders, A. & Nahon, M. (2002). 'The Effect of Forward Vehicle Velocity on Through-body AUV Tunnel Thruster Performance'. Proceedings of Oceans 2002 Conference, MTS/IEEE, Biloxi, MI, USA.

TSL Technology Ltd. (2006). Integrated Thruster Data. http://www.tsltechnology.com/ (Viewed 30 Jan 2009).

Yoerger, D.R., Cooke, J.G. & Slotine, J.-J.E. (1990). 'The Influence of Thruster Dynamics on Underwater Vehicle Behavior and Their Incorporation into Control System Design'. IEEE Journal of Oceanic Engineering, **15**(3), pp. 167-178.