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Experimental Testing of an Autonomous Underwater Vehicle with Tunnel Thrusters

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ABSTRACT

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The abstract should not exceed 200 words and be informative of the purpose, methods, results, and conclusions.

Keywords

Autonomous Underwater Vehicle, Simulation, Tunnel Thruster, Experimentation.

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 systems which use the information recorded by sensors to determine demands for the vehicle actuators. The complexity of these control systems is a function of the sensors and actuators employed and the desired vehicle performance. Furthermore, these vehicles are constrained by the limited energy supply carried onboard.

There are many different types of AUV currently in use and generally these vehicles are designed for a specific purpose. Example missions undertaken by AUVs include oceanographic surveying, mine-sweeping and pipeline inspection. As the performance of these vehicles improves so the desire to use these vehicles in a greater number of scenarios increases. 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.

A key performance indicator for a survey vehicle is the range it can achieve. 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 and the necessary mission dependent payload. This has resulted in a common survey style vehicle design consisting of a torpedo-shaped hull form with a stern mounted propeller and control surfaces for control at speed. These 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. In order to overcome the positive buoyancy at survey speeds the vehicles operate with a small 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 forces to, firstly, maintain a pitch angle to control the positive buoyancy, and secondly, manoeuvre the vehicle in the desired manner. Thus the creation of a multi-purpose vehicle requires additional control devices to provide low speed control. The majority of underwater vehicles use propeller based thrusters to provide low speed control due to their responsiveness, reliability and ability to generate forces throughout the speed range. To maintain the survey efficiency of the vehicle these thrusters can be placed within 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 survey-style configuration with four additional tunnel thrusters

2 TUNNEL THRUSTER PERFORMANCE

The vehicle shown in Figure 1 will need to use the tunnel thrusters for two key tasks. These are the control of the positive buoyancy at speeds below the limit of control surface control and for low and zero speed manoeuvring 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 a higher speed range with a limited range of pitch angle. The exact values applied to these ranges are a function of the detailed design of the 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. The analysis will also be limited to zero pitch as the performance of the tunnel thruster is expected to be relatively consistent over the range of small pitch angles expected at these speeds.

The performance of small diameter tunnel thrusters has been investigated in static conditions (McLean 1991; Cody 1992) leading to the development of a model of the dynamic performance of the thruster (Healey et al 1995). These experiments demonstrated 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 performance of tunnel thrusters in an AUV hull form over the full range of operational vehicle speeds and yaw angles in the range ±90º has been investigated in (Saunders & Nahon 2002). However, for these experiments the thruster was isolated from the vehicle hull form and the forces recorded were those generated by the thruster and not those experienced by the vehicle. These results showed a variation in thrust of around 15% over the range of forward speeds tested.

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

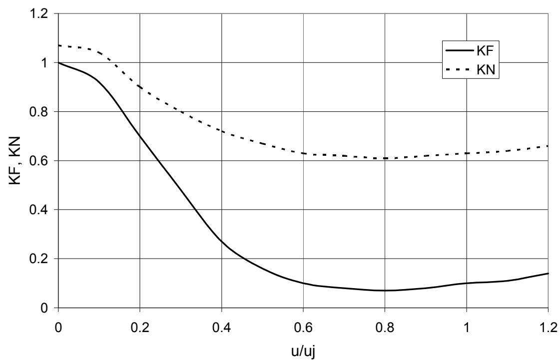

Figure 2 – Force and moment data for a tunnel thruster on a submersible

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.

$$K_F = \frac{F_{T\,@\,Speed\ u}}{F_{T\,@\,Zero\,Speed}} \quad (1a)$$

$$K_N = \frac{N_{T\,@\,Speed\ u}}{N_{T\,@\,Zero\,Speed}} \quad (1b)$$

$$\frac{u}{u_j} = \frac{u}{\sqrt{\frac{T}{\rho A}}} \quad (1c)$$

The data shown in Figure 2 shows a variation in force of up to 95%, which is considerably more than that recorded in (Saunders & Nahon 2002). This indicates that variation in force is not solely due to the performance of the thruster unit itself.

2.1 Lateral Thrusters on Surface Vessels

The performance of a tunnel thruster on a moving underwater vehicle is analogous to the performance of a lateral thruster on a surface vessel. The performance of lateral thrusters has been investigated in (Nienhuis 1992; English 1972; Brix & Bussemaker 1973; Chislett & Björheden 1966). This research includes measurements of the forces and moments on the vessels, simple flow visualisation experiments and pressure measurements around the thruster. These results, and the conclusions drawn, provide an insight into the mechanisms causing the variations 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. However when the vessel is moving forwards the thruster jet is deflected as a function of the relative strength of the jet to 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. The offset of this suction force from the thruster force causes a further variation in moment experienced by the vehicle.

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

2.2 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. In order 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 moment can be calculated according to geometric considerations (Ananthakrishnan et al 1998). Saunders & Nahon (2002) do attempt to modify the model from (Healey 1995) but since this model does not account for ambient flow effects it does not model 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 a survey style AUV.

3 EXPERIMENTAL SETUP

A 2.5m, approximately one-third scale, model of the survey AUV Autosub (Fallows 2004) was modified to accommodate two through-body tunnels, one forward and one aft, as shown in Figure 3. Each tunnel has a diameter equal to that of the thruster mounted within the tunnel and the tunnel is 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 offer symmetrical performance and minimise the blockage in the tunnel caused by the hub. The thrusters were driven using an electronic speed controller with the rotational speed of the thruster controlled by varying the voltage of the signal.

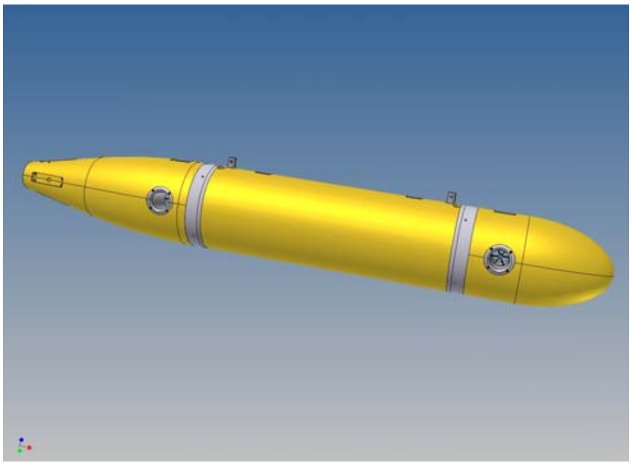

Figure 3 – CAD drawing of the Autosub model showing forward and aft thruster tunnels (control surfaces and stern propulsor not shown)

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 onto a purpose designed and built dynamometer and supporting framework which incorporates four force blocks. 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 to measure drag and side force. Each force block was calibrated using a multi-point calibration using calibrated weights. The signals are digitised and passed to a PC for automated data logging. The data was recorded at 60Hz.

The test plan for the experiments was designed to cover the range of operational conditions expected. This includes testing over a range of forward speed and thruster rotational speed.

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%.

The force generated by the thruster at zero speed was recorded throughout the range of rotational speeds. These results are shown in Figure 4. These results show a linear trend with the square of the rotational speed as expected and closely match the data published by the manufacturer.

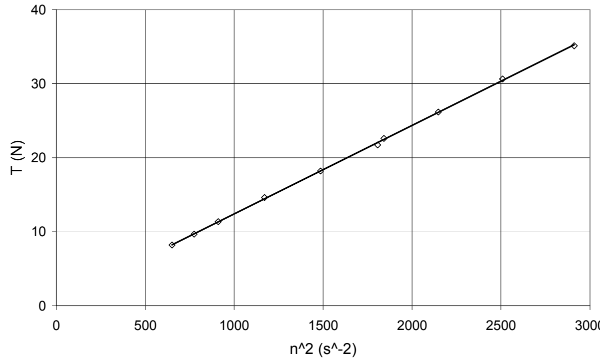

Figure 4 – Tunnel thruster performance under static conditions showing thrust, *T*, against the square of the thruster rotational speed, n^2

The results for the forward and aft thrusters across the range of speed ratio are shown in Figure 5. 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.

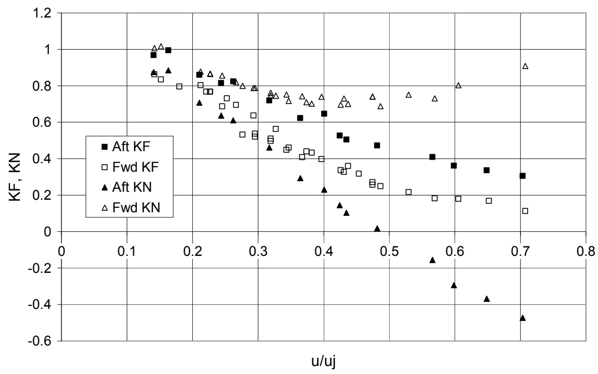

Figure 5 – Tunnel thruster performance for forward (hollow symbols) and aft (solid symbols) thrusters on an AUV moving with a forward speed

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 obtained by (Beveridge 1972) (Figure 2). The differences between the two force curves are an indication of 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 vehicle and consequently differing performance characteristics. Both thrusters were also run at the same time, in the same and opposite directions, and no interaction effects were experienced at the large thruster separation used.

Figure 5 also shows the moments generated by the thrusters to drop off considerably with increasing speed ratio. 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. These are the thrust force generated, assumed to act at the thruster axis, and a suction force, which acts at a variable point as a function of the 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. The suction moment, N_S, is defined as the difference between the expected (zero speed) moment and the moment experienced by the vehicle.

$$F_S = F_{T@Zero Speed} - F_{T@Speed\ u} \tag{2a}$$

$$N_S = N_{T@Zero Speed} - N_{T@Speed\ u} \tag{2b}$$

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

$$x_S = \frac{N_S}{F_S} \tag{3}$$

Figures 6 and 7 show the variation of the centre of action of the suction force, with speed ratio, for the forward and aft thrusters, respectively. These results show that the centre of action of the suction force for the forward thruster moves aft with increasing speed ratio. This movement is towards the central pivot of the vehicle and thus reduces the impact of the suction moment, giving the limited reduction shown on Figure 5. 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 effective moment changes sign as the suction moment dominates the desired thruster moment. The reasoning behind this relatively constant centre of action for the aft thruster is thought to be caused by the truncation of the hull form after the thruster tunnel exit.

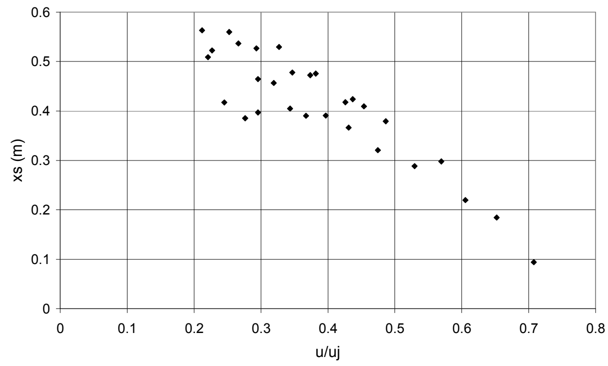

Figure 6 – Centre of action of the suction force, x_S, for the forward tunnel thruster against speed ratio, u/u_j

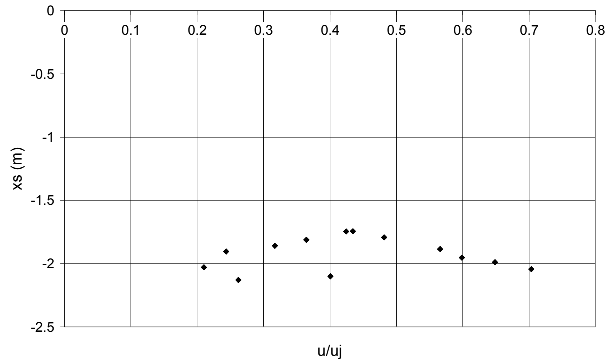

Figure 7 – Centre of action of the suction force, x_S, for the aft tunnel thruster against speed ratio, u/u_j

The drag force on the vehicle was also recorded during these experiments. Figure 8 shows the increase in volumetric drag coefficient, compared to the thruster-off case, against speed ratio.

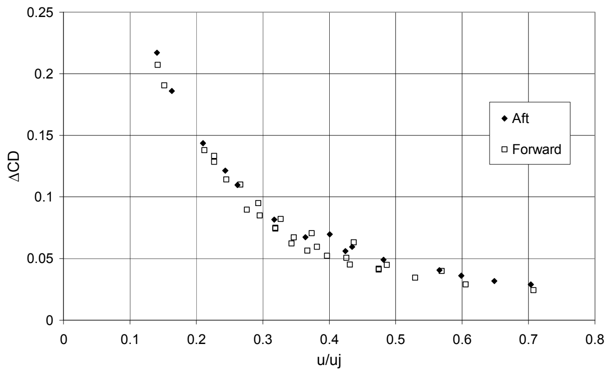

Figure 8 – Volumetric drag coefficient increase, ΔC_D, against speed ratio, u/u_j, for the forward (hollow symbols) and aft (solid symbols) thruster operation

These results show that the increase in drag decreases as speed ratio increases. 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 drag at low speeds is small and hence a large increase in drag coefficient does not correspond to a large increase in actual force.

5 TUNNEL THRUSTER MODELLING

To accurately simulate 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) states 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) concludes 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 has been fitted to the force results of the form:

$$K_F = \exp\left[-c\left(\frac{u}{u_j}\right)^2\right] \tag{6}$$

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. For the forward thruster $c \approx 7$ and for the aft thruster $c \approx 3$.

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

$$N = F_T x_T + F_S x_S \tag{4}$$

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 determined 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 6, show some agreement with this conclusion, giving a model of the form:

$$x_S = x_T - kD\frac{u}{u_j} \tag{5}$$

However the results for the aft thruster do not follow this linear trend and hence a constant value is applied here. These results show that it is important to account for the truncation of the body when selecting the model to be used for the suction moment arm.

6 CONCLUSIONS

To create a multi-purpose AUV capable of both survey-style missions and low speed interaction with the environment encountered requires the addition of further control devices to common survey AUV configurations. In order to retain the existing survey efficiency where possible these additional control devices can take the form of through-body tunnel thrusters. 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 tunnels on a torpedo-shaped AUV model. 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.

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

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