Second International Symposium on Marine Propulsors
smp'11, Hamburg, Germany, June 2011

The performance of vertical tunnel thrusters on an autonomous underwater vehicle operating near the free surface in waves

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ABSTRACT
When operating near the free surface in waves, underwater vehicles can experience large forces acting on the body which can cause the vehicle to move undesirably. To overcome these forces, and keep station with minimal disturbance, actuators fitted to the vehicle are used. To develop a suitable controller, the performance of said actuators must be known. This paper shows that as a vertical tunnel thruster approaches the free surface, the thrust generated decreases. Experimental and simulated data is presented and reasons for the reduction in effective thrust discussed. Further to this, the performance of the Delphin2 AUV operating in waves is analysed and suggestions made for improving performance.

Keywords
Rim-driven thruster, AUV, free surface, waves

1 INTRODUCTION

Flight style Autonomous Underwater Vehicles (AUVs), such as the Remus 100 and Autosub6000, are ideally suited to performing high speed missions (>1m/s), requiring the vehicle to survey large areas of the seabed (McPhail et al 2010). These vehicles use rear mounted control surfaces to manoeuvre; resulting in the vehicle becoming uncontrollable at slow speeds. To enable survey style vehicles to operate at slow speeds, several vehicles have been fitted with vertical through-body tunnel thrusters (C-Scout, Delphin2 etc), becoming hover capable flight style AUVs.

With the development of more adaptable underwater vehicles, it is a requirement that the capabilities of each vehicle be fully realized through the use of highly capable control systems. To achieve this level of control, the system must be fully understood and modelled.

When operating near the free surface, AUVs are subjected to large forces developed by surface waves causing the vehicle to move undesirably (Edgar et al 1998). The magnitude of these disturbances varies according to the vehicles depth and orientation and the sea state.

Although many models now exist for underwater vehicles, they often neglect the effect that the actuator dynamics have on the manoeuvring capability. The Delphin2 AUV is fitted with two 70mm rim driven through-body vertical tunnel thrusters, one forward, and one aft. During normal (at depth) operations both thrusters are used to overcome the vehicles positive buoyancy to maintain and control depth. It has been observed that during the operation of the Delphin2 AUV that thruster speed is required to be higher to dive from the surface than when at depth.

With sufficient knowledge of the performance of the vertical tunnel thrusters in waves, and at various depths, it should be possible to reduce or eliminate the magnitude of the undesirable heave and pitch motions produced by surface waves.

1.1 Delphin2 AUV

The Delphin2 AUV (Phillips et al 2010) (Figure 1) has been developed by post-graduate students as a collaboration between the University of Southampton and the National Oceanography Centre, Southampton. The purpose of the vehicle is to provide an experimental platform for developing new mission planning programs and low-level controllers and also for studying the hydrodynamics of AUVs.

The vehicle is over-actuated with; two vertical and two horizontal tunnel thrusters, a rear ducted propeller, and four independent control planes. The hull design is a scaled version of the hull used by Autosub6000, providing a low drag resistance against forward motion. The combination of the low drag hull and multiple actuators enable Delphin2 to perform hovering ROV type precision control with long range survey type missions.

This work focuses on improving the depth/altitude control of Delphin2 whilst hovering near the free surface using the vertical tunnel thrusters.

Figure 1 - Computer rendering of Delphin2 AUV

2 EXPERIMENTAL SETUP

In order to study the performance of the vertical tunnel thruster at different depths, new experimental data is required. To achieve this, a new tunnel thruster assembly (Figure 2) has been built and several sensors used to measure values of interest. The tunnel thruster is mounted vertically in the frame and includes an outer plastic tube of the same diameter as the Delphin2 hull.

The experiments were conducted at the Lamont towing tank at the University of Southampton. This tank measures 30 x 2.4 x 1.2 meters deep.

Figure 2 – Thruster assembly submerged in Lamont Towing tank

2.1 Thruster

Four tunnel thrusters are used on the Delphin2 AUV; two for heading control and two for depth control. The thrusters (Figure 3) are produced by TSL and are rim driven using a 50W brushless DC motor which is controlled using an electronic speed controller (ESC), also produced by TSL. Set-point demands are sent to the ESC from a PC via serial. The ESC can also be programmed to provide feedback for the current motor speed.

Figure 3 – 70mm TSL brushless 50W tunnel thruster

2.2 Sensors

A load cell, rated to 5 Kg, is used to measure the vertical thrust. This was connected between the thruster assembly and the walkway across the tank. The output voltage of the load cell was amplified by a gain of 100 using a Fylde 351UA amplifier so as to improve the effective resolution of the DAQ.

Two differential pressure measurements were taken during these tests; one across the propeller in the tunnel, and one between the top and bottom of the large outer tube, Figure 4. An Omega PX409 differential pressure transducer (rated: 0 – 2500 Pa) was used to make these measurements. The transducer outputs a 0-5V signal which can be directly measured using the DAQ.

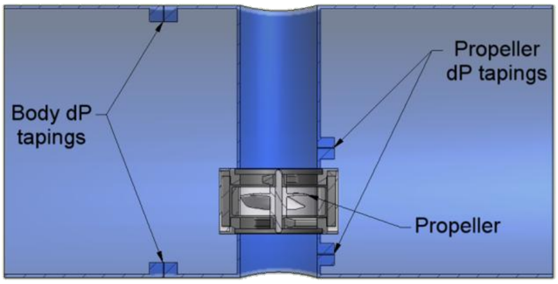

Figure 4 – Pressure tapings on thruster assembly

2.3 Data acquisition

The thruster control and data acquisition of the sensors is conducted using the computer from the Delphin2 AUV. This enabled the logging of thruster set-point, thruster speed, differential pressures, and the load cell voltage all on the one system.

To measure the voltages produced by the differential pressure transducer and the load cell, a National Instruments USB-6211 data acquisition board was used. This provided 24-bit resolution and a sample rate of 500Hz.

2.4 Sensor calibration

The pressure transducer came with a calibration certificate provided by its manufacturer. As the transducer was bought specifically for these tests, it was assumed that this calibration is correct.

The load cell calibration was performed each time the frame was adjusted for a specific depth. As can be seen in Figure 5, the performance of the load cell is linear.

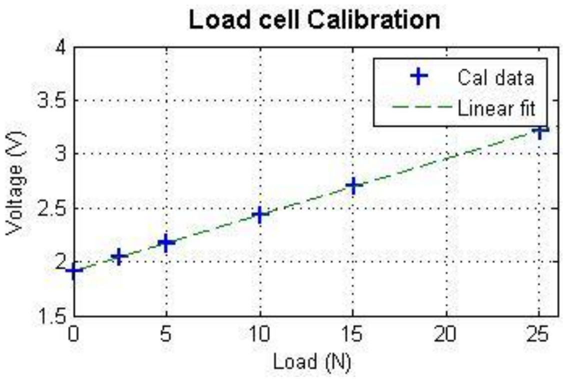

Figure 5 – Load cell calibration example. $R^2 = 1$.

3 THRUSTER MODEL

Much work has been produced on the modelling of thruster performance, both for steady state and transient states. A good review of several models is given in (Whitcomb 1999). For the purposes of this work, the thruster will be modelled as a steady-state system and the transient effect ignored.

3.1 Preliminary results

As would be expected, generated thrust is linearly proportional to thruster speed squared, see figure 6. Thus:

$$T = k_t \omega |\omega|$$

Where: T = Thrust (N)

k_t = Thrust constant

ω = Thrust speed (rpm)

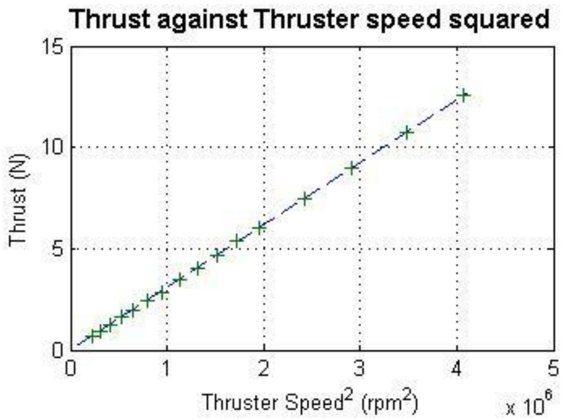

Figure 6: Thrust against thruster speed squared. R-squared value for linear fit: 0.9999. Data from 40cm depth test.

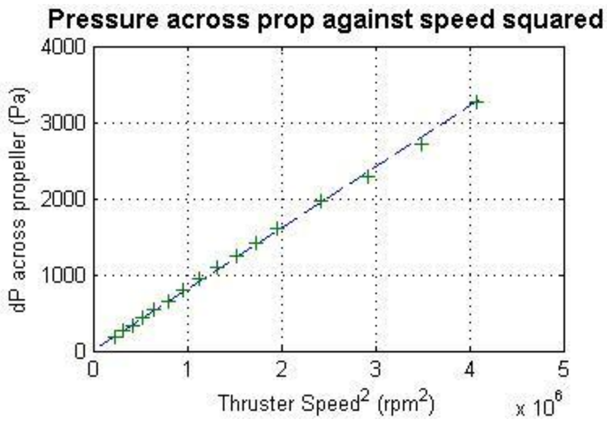

Figure X: Pressure across propeller against thruster speed squared. R-squared value for linear fit: 0.9987. Data from 40cm depth test.

Figure 7 shows that the pressure across the propeller is linearly proportional to the thruster speed squared. Figure 8 plots the data for four different set-points resulting in four different thruster speeds. What is interesting in this plot is that it clearly shows the reduction in generated thrust as the thruster approaches the free surface however the effect becomes negligible at high thruster speeds. This non-linearity is the focus of investigation for this work as it is likely have a significant effect on the vehicle dynamics, particularly when operating with disturbances such as surface waves.

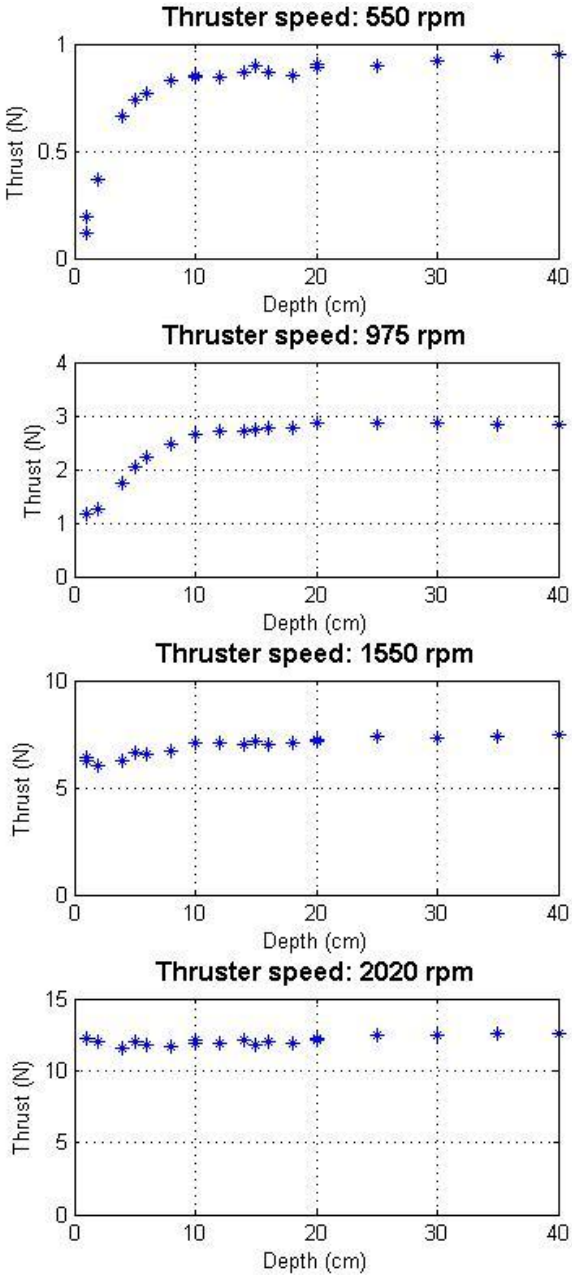

Figure 8 – Thrust against Depth for four thruster speeds

3.2 Propeller performance

The effective thrust experienced by the tunnel thruster assembly is the sum of both the force generated by the propeller and the forces generated by the external fluid dynamics acting on the outer body. In this section the propeller will be analysed separately from the body.

Using the general thrust equation:

$$T = \dot{m}_{exit}V_{exit} - \dot{m}_{in}V_{in} + (p_{exit} - p_{in})A_{exit}$$

Where: $\dot{m}$ = Mass flow rate (kgs^{-1})
V = Flow velocity (ms^{-1})
p = Pressure (Pa)
A = Area (m^2)

It can be seen that the thrust, T, is a function of the change in mass flow rate, velocity and pressure across the thruster. As the propeller is fitted within a tunnel, the average velocity and flow rate just before and after the propeller is equal, assuming the fluid is incompressible. Therefore the thrust equation can be simplified to:

$$T = (p_{exit} - p_{in})A_{exit}$$

It is expected that the effective thrust experienced by the tunnel thruster assembly when at depth is dominated by the thrust generated by the propeller and the effect of flow around the body is negligible. Figure 9 plots the differential pressure across the propeller multiplied by thruster cross sectional area, against thruster speed squared. Also in figure 9 is the effective thrust on the tunnel thruster assembly (measured using the load cell). As can be seen, the calculated thrust and the effective thrust correlate accurately. The calculated thrust relies on the assumption that the differential pressure measurement is the same as the average pressure across the tunnel diameter.

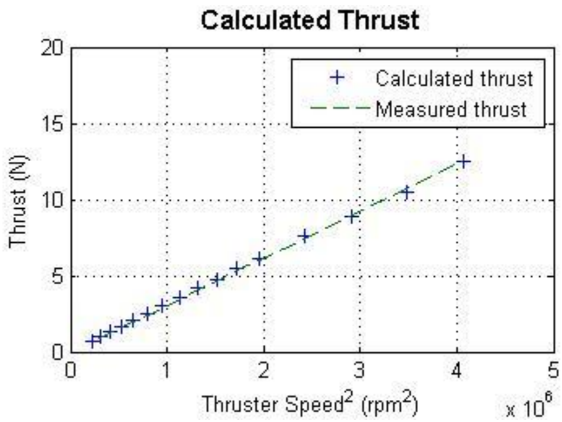

Figure 9: Calculated thrust against thruster speed squared

With this assumption, the thrust generated by the propeller can be calculated using the differential pressure measurements. Figure 10 plots the calculated propeller thrust against depth for four different propeller speeds. All four plots show no obvious correlation with depth. For the rest of this work it will be assumed that the propeller thrust is not a function of depth and the focus will be on analysing the flow around the outer body.

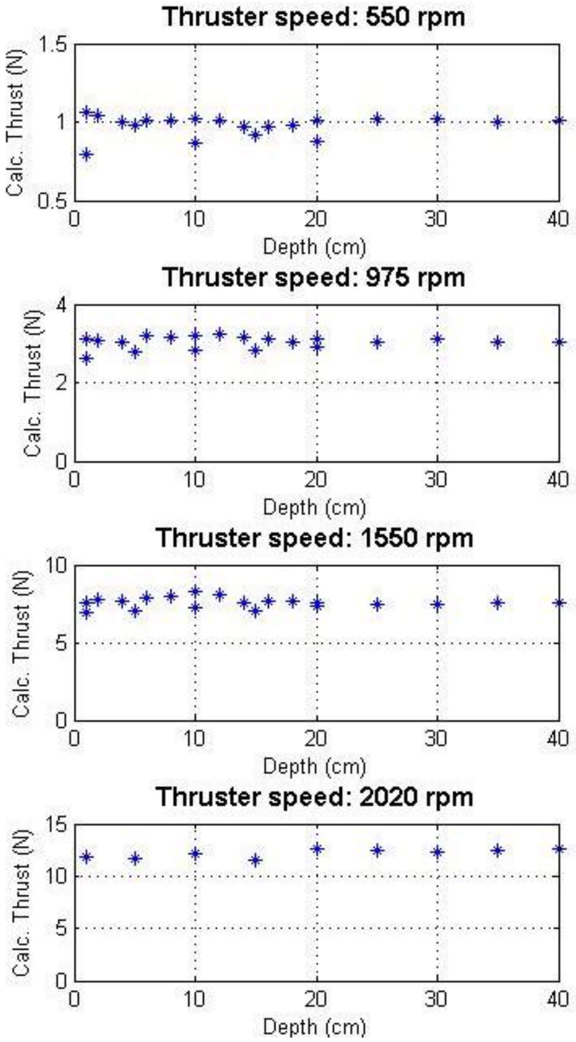

Figure 10 – Calculated thrust against Depth for four thruster speeds

3.3 External flow affect on effective thrust

Due to the complexity of the flow near the free surface it would not be advantageous to try to produce an accurate mathematical model. A hypothesis will therefore be stated and experimental and simulation results used to evaluate it.

Hypothesis:

A. The reduction in effective thrust on the tunnel thruster assembly, near the free surface, is due to an increase in the velocity of the flow across the top of the assembly body.
B. The increased flow velocity causes a negative pressure gradient between the top and bottom of the body resulting in a force towards the free surface which works against the propeller thrust, thus reducing the effective thrust on the tunnel thruster assembly.
C. As depth increases, the high velocity flow is further away from the body due to a larger boundary layer and so the negative pressure gradient across the body becomes less.

D. As the thruster speed increases, the fluid on the free surface is raised above its normal level, resulting in a larger boundary layer around the body and so the effect of the free surface on effective thrust will be less at high thruster speeds than low thruster speeds.

To analyse these hypotheses a combination of experimental and computational fluid dynamics (CFD) simulation data will be used. The simulation data has been conducted using a structured mesh.... alex?

3.3.1 Hypothesis A

Due to the flow being highly turbulent and unsteady it would be difficult to accurately measure the direction and magnitude of the flow experimentally. Therefore the CFD simulations will be relied upon to provide information regarding the flow profiles around the tunnel thruster assembly…. alex?

3.3.2 Hypothesis B

The differential pressure between the top and bottom of the body was measured one diameter away from the inlet and exit of the tunnel thruster (Figure 4). The transducer was fitted with the positive port connected to the bottom of the body, thus a positive value means the pressure at the bottom of the body is larger than the base.

Figure 11 plots the differential pressure against depth for several different thruster speeds. Clearly from 0 to 10 cm in depth the differential pressure is significantly highly than deeper tests. It is also noted that the differential pressure increases with thruster speed with the maximum recorded pressure at 725 rpm at 1cm depth. Above this speed the differential pressure reduces, as hypothesis D states.

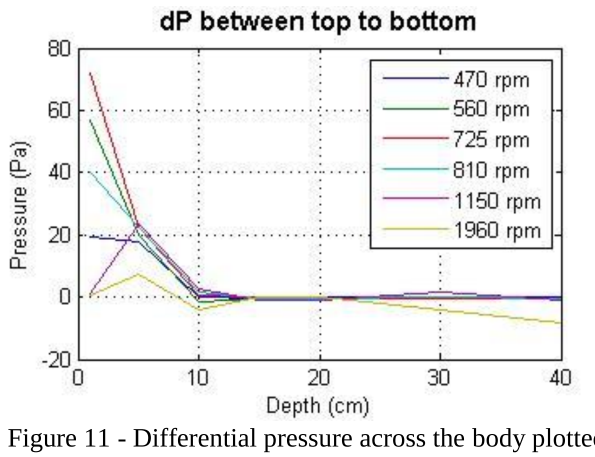

Figure 11 - Differential pressure across the body plotted against depth for several different thruster speeds

CFD work...

3.3.3 Hypothesis C

Figure 11 has shown the differential pressure across the body decreases with depth however, this does not conclude that it is due to a larger boundary layer developing. Using the CFD...

3.3.4 Hypothesis D

Again, similar to hypothesis C and D, figure 11 presents the experimental data that supports the hypothesis. Above the thruster speed of 725 rpm the differential pressure decreases. It was also observed that the higher the thruster speed, the higher the free surface was raised above its normal level, figure 12.

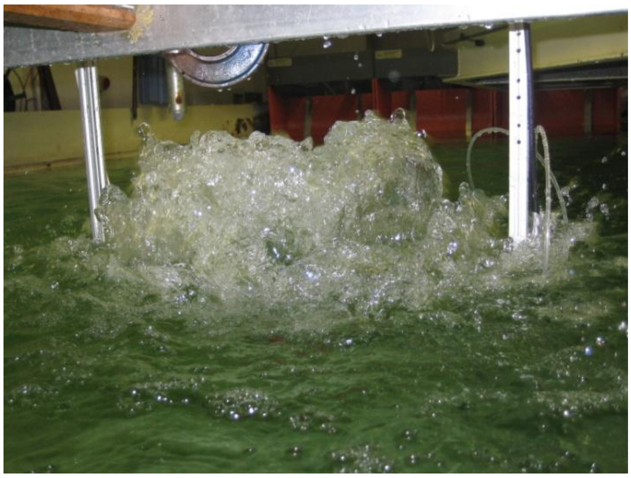

Figure 12 – Observation of the free surface was raised from normal level at high thruster speeds

4 AUV OPERATION IN WAVES

Previous work has shown that surface waves act on the body of underwater vehicles causing a disturbance (Edgar et al, 1998), (Ananthakrishnan, 1998) and (Riedel, 2005). The previous work has analyzed and modelled the forces generated on the AUV by the surface waves; however the effect on thruster efficiency has not been studied.

To study the capability of the Delphin2 AUV to maintain a fixed altitude (distance from seabed), a series of tests were conducted (figure 13). These tests have been performed in the Southampton Solent Towing Tank (60 x 3.7 x 1.85 metres deep), using a HR Wallingford wave-maker.

4.1 Experimental Setup

The Delphin2 AUV was placed in the towing tank without waves. It was then programmed to maintain a heading directly facing the oncoming waves. The altitude was varied through the tests and was specified to the mission controller before each test. The standard low-level controller that is tuned for operation at depth was used.

The generated waves are regular and the wave amplitude is fixed at 0.1 m for all the tests (except calm water tests). The wave frequency is varied between 0.5 and 1.5 Hz, resulting in waves lengths of 0.7 to 6.25 m. Each test lasted 5 minutes.

Sensors onboard the AUV are used to record; altitude, depth, pitch, roll and heading. Altitude is measured using a Tritech Micron Echo Sounder DST – Ultra Compact Altimeter. This provides a sample rate of approximately 30Hz and a measurement resolution of 0.01 metres. Pitch, roll and heading are all measured using an OceanServer OS5500 digital compass. The digital

compass also has a 24 bit A/D convertor which is used to measure the voltage from a pressure transducer. This pressure is used to calculate depth.

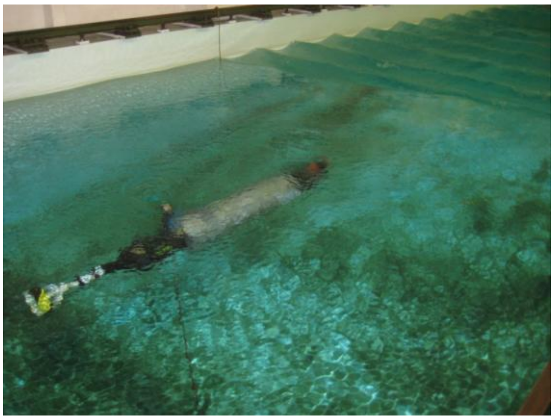

Figure 13 – Delphin2 AUV at depth and heading as first waves approach

4.2 Experimental Results

For these tests, the focus is on maintaining altitude and minimizing disturbances on zero pitch. Two set altitudes were tested; 1.2 and 1.5m, and a series of tests were also conducted with the AUV altitude controller switched off (AUV floating on surface).

The buoyancy of the vehicle is always positive and is typically not adjusted between tests; therefore the buoyancy was set to its standard value. This value was back calculated from the test data using the average thruster speed during a fixed altitude test with no waves. The average thruster speed is 690 rpm, thus the combined force generated to overcome the buoyancy by the two thrusters is 2.77 N.

First a fast Fourier transform was performed on the pitch and altitude data, Figure 14. This concluded that the frequency of the main disturbance to the vehicles pitch and altitude was the same as the frequency of the surface waves.

The magnitude of the disturbances has been calculated from the data. Figure x plots the amplitude of the heave disturbance from the waves for three different altitudes. It should be noted that the magnitude of disturbance increases with decreasing wave frequency. Also, the disturbances from the tests at 1.5m altitude are approximately the same as the tests conducted on the surface. During the 1.5m altitude tests it was observed that the top of the vehicle was breaking the surface during the trough of the wave. It can therefore be concluded that the altitude controller failed at this altitude due to a combination of both the forces of the waves and the reduction in effective thrust as the vehicle approaches the free surface.

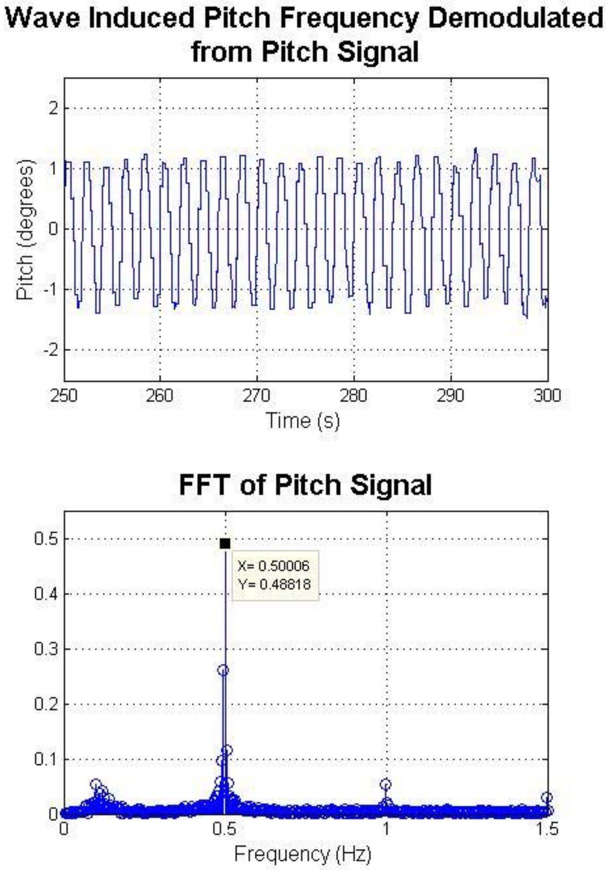

Figure 14 – Data from test at 1.2m altitude (0.4m depth) and 0.5 Hz wave frequency. Top: Pitch against time, Bottom: FFT of pitch signal showing dominant disturbance frequency is the same as the surface wave frequency

From this data it is clear that the closer to the surface the vehicle is required to operate, the more difficult it will be to control.

Further development of a controller incorporating the thruster model from section three may improve the performance of the vehicle during station keeping operation in waves. However, it is clear that the forces generated by the waves are enough to cause significant disturbance as can be seen for the tests at 1.2 m altitude. Here the thruster performance should not be significantly diminished by the free surface interaction, yet the disturbance to pitch and heave is still significant.

For development of control for work in waves, it could be beneficial to develop a model that could predict the oncoming waves and thus enable the controller to react quicker. This is likely to work in a laboratory environment, but at sea the waves are not regular and are thus much more difficult to model accurately.

To improve future performance of the vehicle operating in waves it would be advantageous to develop a thruster model which included the transient dynamics for motor speed and thrust. This could then have a separate thrust controller built on so as to enable faster thrust response time.

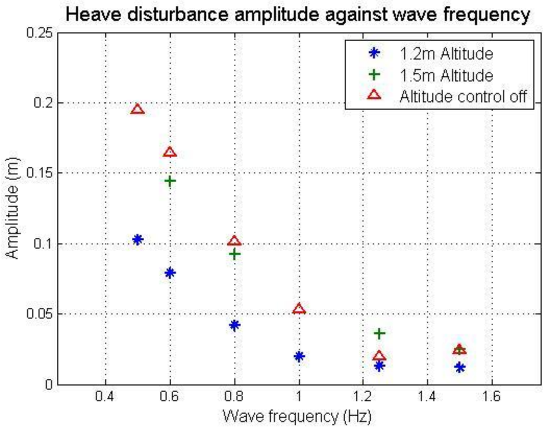

Figure x – Average disturbance amplitude against wave frequency for altitude controller set to 1.2m, 1.5m and off.

5 CONCLUSIONS

From section three, it is clear that the effective thrust acting on the thruster assembly diminishes as the thruster approaches the free surface. From the experimental data, it can be concluded that the thrust generated by the propeller of the thruster does not changes as a function of depth but instead the flow induced by the thruster causes changes in static pressure across the vehicle body which acts against the thrust force.

Section four shows that as an underwater vehicle approaches the free surface with waves, the disturbance on the vehicle will be the same as the frequency of the surface waves. It also concluded that, for regular waves acting on the Delphin2 AUV, as wave frequency decreases the magnitude of the disturbances increases. But the main point that must be taken from this section is that above a certain level of disturbance the altitude controller failed. This is due to a combination of; larger disturbance forces from the waves, and lower actuator forces that would be used to counter the disturbances.

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