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Publisher's version / Version de l'éditeur:

AUV 2010, 2010-09-01

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Experimental flight stability tests for the horizontal flight mode of a hybrid glider

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Abstract—The stability of a glider during flight in the horizontal plane is examined. An existing drift-at-depth behaviour is used to control the depth and pitch of the vehicle while the auxiliary propulsion module provides the motive force. Experimental depth controller tests are presented here for fresh water. Additionally, the experimental horizontal flight results in a fresh water test tank are presented. These results show the initial ability of the hybrid glider to maintain a stable path during horizontal flight.

I. INTRODUCTION

Over the last ten years autonomous underwater gliders have become increasingly useful for oceanographic research because of their ability to lower operational expenses, increase range and endurance [1]. Gliders use an active buoyancy control system combined with a set of fixed wings to move vertically and horizontally, in a saw tooth like pattern through the water column [2], [3], [4]. The endurance of these underwater vehicles varies from weeks to several months and even longer in the case of the thermal glider [4]. In contrast, currently available propeller driven autonomous underwater vehicles (AUVs) achieve an endurance ranging from hours to days. This stark contrast can mostly be attributed to a purpose built system and to the low speed at which the gliders move [5] and [6]. Gliders typically move at horizontal speeds of about 0.3 m/s compared to propeller driven AUVs which typically move at average speeds greater than 1.0 m/s. The low speed capability can create significant problems when operating in areas of strong water currents which exceed the glider's maximum forward speed. If the direction of the currents is known a priori or measured in situ [7] the missions can be designed to either avoid these areas or to take advantage of them. In this case the operator must redirect the glider to better deal with the current by moving away from that region or, in the case of significant vertical stratification, try to operate below/above the expected layer of highest lateral velocities. However, in the case of unknown currents they can pose a significant risk to the successful execution of the mission plan. These issues have given rise to the idea of the hybrid glider which combines the gliding behaviours of traditional underwater gliders with the propeller driven behaviours of AUVs.

The hybrid glider is a standard 200 m Slocum electric

glider augmented by a low-power propeller-driven propulsion system. This propulsion system is integrated into the glider at the rear of the vehicle, replacing the 500 gram emergency drop weight. The introduction of the propulsion force at the rear of the vehicle has the potential to create instabilities in pitch and therefore has the potential to have a detrimental effect on the ability of the hybrid glider to hold a constant depth while maintaining forward speed.

To test the stability of the vehicle, a pre-existing vehicle behaviour, named drift-at-depth, was used. This behaviour or control mode uses the buoyancy engine to keep the glider within a certain depth band and uses the pitch controller, a moveable internal battery pack, to servo a desired pitch. The controllers for pitch and depth control use dead-bands and proportional gains to achieve an appropriate response of the system. For our purpose the control parameters for this mission were tuned experimentally. The Memorial University of Newfoundland (MUN) deep water test tank (L: 3.6 m, W: 3.6 m, D: 3.9 m) was used to tune the two control loops, pitch and depth, for faster response time and tighter dead-bands. The propulsion module is controlled by the glider's science computer and not the glider's control computer. This allows us to activate the propulsor similar to the activation of a sensor, as a function of the vehicle control state. In our case the propulsion module is turned on only when the glider is operating in the "drift-at-depth" state.

For our mission the glider dives to a predetermined depth using the nominal glider dive mode and once reached, it engages the modified drift-at-depth behaviour including the propulsion module. Using National Research Council's Institute for Ocean Technology (NRC-IOT) Ocean Engineering Basin (L: 70 m, W: 35 m, D: 3 m) we conducted a total of 25 tests. During these tests five different missions were flown, with each mission having a different motor setting that corresponds to horizontal speeds ranging from approximately 0.2 m/s to 0.6 m/s with each mission repeated five times. During these tests the rudder angle was set to be at zero degrees for straight-ahead travel and minimum resistance. For the purpose of these tests we installed an inertial measurement unit to measure the vehicle's attitude, angular rates and accelerations.

The results of these tests show that for the lower velocities,

i.e. 0.2 m/s to 0.4 m/s, the vehicle is capable of controlling its pitch and depth over the test distance. For the higher speeds the distance of 30 m is not sufficient to conclusively show stable flight, however, the data shows no extreme instabilities being present. To expand on these tank tests, field trials are being conducted in the ocean off the coast of Newfoundland where the glider is driven at a predetermined depth for 10 minutes tests.

II. DEPTH CONTROLLER CHARACTERISATION

The trajectory of an underwater glider is typically in a sawtooth-like pattern where the vehicle is gliding downwards and upwards. This pattern is not conducive to flying horizontally using the auxiliary propulsion module. To allow for horizontal flight two of the controllers which must be configured are the depth and pitch controllers. For a glider with zero advance velocity, the pitch and depth controllers may be considered independent. This assumption does not hold for non-zero advance velocities as the pitch and depth are strongly coupled in this case. However, to tune the controllers the assumption is used as a starting point.

Fig. 1. Depth controller structure

For testing purposes the drift-at-depth behaviour was used as it includes a pitch controller and depth controller. A diagram of the depth controller structure is shown in Fig. 1 where c_depth is the desired depth control point and $c_deadband$ is the depth deadband for determining the hovering state. Initially, the neutral ballast lookup table mode was used but this did not allow for a predictable start value for $x_hover_ballast$, the output to the ballast system, as the table is unpopulated for the first dive after the glider is turned on making the response unpredictable. Therefore, an initial $x_hover_ballast$ value V_o based on experimental tests was used. The controller steps $x_hover_ballast$ by the ballast pump delta value δ_{bp} depending on which state it determines the glider to be in. If the glider is outside of the hovering depth zone defined by c_depth and $c_deadband$, the controller will decrement $x_hover_ballast$ if it is above the depth zone and moving up and will increment $x_hover_ballast$ if it is below the depth zone and moving down. If the vehicle is inside the depth zone there are two additional states in which the controller will change $x_hover_ballast$, moving down too quickly and moving up too quickly. The controller determines these states

by comparing the measured depth rate $\dot{z}$ with the hovering depth rate $\dot{z}_h$ which is calculated using the user configurable input hovering depth rate gain $\dot{z}_{in}$ as in

$$\dot{z}_h = \dot{z}_f \dot{z}_{in} \quad (1)$$

where the factory set hovering depth rate $\dot{z}_f = 0.1425$ m/s by default. If the glider is moving up and $|\dot{z}|$ is greater than the $\dot{z}_h$, the glider is moving up too fast and $x_hover_ballast$ is incremented. Similarly, if the glider is moving down and $|\dot{z}|$ is greater than the $\dot{z}_h$, the glider is moving down too fast and $x_hover_ballast$ is decremented. If the glider passes through all these states it is assigned to be in or hovering towards the drift depth zone in which the $x_avg_hover_ballast$ argument is updated for the neutral ballast lookup table.

The depth controller was characterised experimentally in the deep water test tank (L: 3.6 m, W: 3.6 m, D: 3.9 m) at MUN by iterating the input parameters to the controller around the default vehicle parameters. Four tests were run to tune each of the parameters. The ballast pump delta value δ_{bp} tuning results are shown in Fig. 2. From these tests the resultant ballast pump delta value $\delta_{bp} = 2$. These tests also show significant spiking in the depth sensor reading. The intermittent spikes when the vehicle passes 2 m were determined to be a result of the depth state changing from or to the at-surface state. The periodic spikes were determined to be a result of the Iridium device cycling power while the vehicle was in the at-surface state. The tank's limited depth required changing the default at surface depth of 2 m to 0.5 m which prevents the depth sensor reading from spiking.

Fig. 2. Depth controller ballast pump delta δ_{bp} tuning tests

The hovering depth rate $\dot{z}_{in}$ tuning results are shown in Fig. 3.

The ballast bump initial value V_o tuning results are shown in Fig. 4.

From these tests the resultant input parameters were taken as the ballast pump delta value $\delta_{bp} = 2$, the ballast pump initial value $V_o = -30$ cc and $\dot{z}_{in} = 0.1$. It should be noted that the

Fig. 3. Depth controller hovering depth rate $\dot{z}_{in}$ tuning tests

Fig. 4. Depth controller initial ballast pump volume V_o tuning tests

depth reading spiking was discovered half-way through the $\dot{z}_{in}$ tests and was present for all of the δ_{bp} tests therefore the resultant values may be affected.

The pitch controller uses several limits and a proportional gain to maintain a set-point value using an internal mass shifting mechanism [8]. The controller inputs are taken from [8] as $u_{pitch_max_delta_battpos} = 0.5$ and $u_{pitch_ap_gain} = -0.5$ where the $u_{pitch_max_delta_battpos}$ argument is the maximum change in inches for the mass shifting actuator and the $u_{pitch_ap_gain}$ argument is the proportional gain for the controller. Additional arguments that were tuned include $u_{pitch_ap_deadband} = 0.001$ which is the deadband for the input to the controller in radians and $f_{battpos_deadzone_width} = 0.03125$ which is the deadband for the output to the mass shifter mechanism in inches.

Using these input parameters a test mission was run three times in the deep water tank to verify the stability of the pitch and depth controller. The results of these tests are shown in

Fig. 5 and in Fig. 6.

Fig. 5. Depth measurements during the drift-at-depth test missions in the deep water test tank at Memorial University of Newfoundland

From Fig. 5 it is shown that the depth controller reaches the hover depth zone of 2 m with a dead-band of 0.2 m within 5 minutes in all cases. Additionally, the maximum overshoot is limited to 0.5 m.

Fig. 6. Pitch measurements during the drift-at-depth test missions in the deep water test tank at Memorial University of Newfoundland

During these tests it was noticed that there was a natural pitching resonant frequency where the glider would oscillate slowly when disturbed. The fast Fourier transform (FFT) of the pitch data from Fig. 6 is shown in Fig. 7

The FFT calculation shows a spike in the amplitude of the pitch response at frequencies of around 0.05 Hz to 0.06 Hz corresponding to a period of roughly 20 seconds and again around 0.005 Hz corresponding to a period of roughly 200 seconds. The higher frequency period of oscillation is attributed to the separation of the centre of gravity and buoyancy of

Fig. 7. Fast Fourier transform of the pitch measurements during the drift-at-depth test missions in the deep water test tank at Memorial University of Newfoundland

the glider and the viscous damping of the vehicle while the lower frequency oscillations are the settling frequency of the controller. These tests show the glider's ability to control the pitch and depth under zero advance velocity and give modified values for the depth controller parameters.

III. DRIVE AT DEPTH RESULTS

To evaluate the stability of the hybrid glider during horizontal flight the glider was flown using the auxiliary propulsion module and the tuned drift at depth behaviour from Section II. Using the NRC-IOT's Ocean Engineering Basin (OEB) (L: 70 m, W: 35 m, D: 3 m) a total of 25 tests were performed. During these tests five different missions were flown, each mission having a different motor setting corresponding to speeds of 0.2 m/s to 0.6 m/s. The propulsion module for these missions turns on during the hovering state of the mission which lasts for a specific time such that the total distance covered is 30 m. A depth of 1.6 m was set as it is approximately halfway between 0.5 m and 3 m. Tests were flown with a fixed rudder angle of zero degrees for straight ahead travel. The inertial measurement unit was also installed in the vehicle to record the vehicle's attitude, angular rates and accelerations. The depth during the hovering behaviour until the behaviour terminates is shown in Fig. 8

The results in Fig. 8 show the glider's depth is well controlled for the 0.2 m/s test. As the velocity increases the lift on the vehicle increases shown by an increase in the amplitude of the depth oscillations. At slower speeds the lift acts to stabilise the depth controller when compared with the MUN deep water test tank tests in which the glider had zero advance velocity. The pitch results for the same tests are shown in Fig. 9

The pitch results show the vehicle is able to control the pitch to zero degrees. There are several instances where a sudden decrease in the pitch for 0.4 and 0.6 m/s is present.

Fig. 8. Depth results for the hybrid glider flying 30 m horizontally at 1.6 m depth in the Ocean Engineering Basin. From top to bottom the advance velocity of the vehicle is 0.2 m/s, 0.3 m/s, 0.4 m/s, 0.5 m/s and 0.6 m/s.

Fig. 9. Pitch results for the hybrid glider flying 30 m set to a pitch angle of zero degrees. From top to bottom the advance velocity of the vehicle is 0.2 m/s, 0.3 m/s, 0.4 m/s, 0.5 m/s and 0.6 m/s.

This pitching disturbance is also visible in the depth figure for the same velocities as sudden change in depth. However, these disturbances are caught by the controller and corrected. The natural pitching motion of the vehicle is also present in this data as shown by the fast Fourier transform (FFT) of the pitch data shown in Fig. 10

The natural pitching motion peak still appears at around 0.05 Hz corresponding to a period of around 20 s. Additionally, the amplitude of the oscillations increases with increasing advance velocity. However, in the FFT analysis of the pitch data the total sampling time of each test must be taken into consideration to establish the reliability of the lower end frequencies. It is considered that frequencies corresponding to periods less than half of the total sampling time are not reliable.

Fig. 10. Fast Fourier transform results of the pitch data from the Ocean Engineering Basin tank tests. From top to bottom the advance velocity of the vehicle is 0.2 m/s, 0.3 m/s, 0.4 m/s, 0.5 m/s and 0.6 m/s. The black vertical lines indicate the minimum frequency corresponding to a period equal to half of the total sample time

Another variable which must be considered is change in roll due to the applied torque from the motor. The raw roll data is plotted as a time series in Fig. 11

Fig. 11. Roll results for the hybrid glider flying 30 m in the OEB test tank. From top to bottom the advance velocity of the vehicle is 0.2 m/s, 0.3 m/s, 0.4 m/s, 0.5 m/s and 0.6 m/s.

From Fig. 11 the roll of the vehicle is seen to increase with the applied torque. The increase in roll is balanced with the restorative force due to the righting moment. The righting moment may be calculated in this case as in (2)

$$H = \frac{\tau_m}{F_g \sin(\phi)} \quad (2)$$

where H is the righting moment arm, τ_m is the motor torque, F_g is the force due to gravity and ϕ is the roll. This

calculation is applied to the data shown in Fig. 11 using the measured roll and torque to find the righting moment for the OEB tank tests as in Fig. 12. For this calculation the vehicle mass was measured to be 52 kg.

Fig. 12. Righting moment results for the hybrid glider flying 30 m in the OEB test tank. From top to bottom the advance velocity of the vehicle is 0.2 m/s, 0.3 m/s, 0.4 m/s, 0.5 m/s and 0.6 m/s.

The resultant righting moment is shown to be around $2E-3$ m for advance velocities for 0.4-0.6 m/s. However, the noise in the roll measurements caused a significant degree of noise in the calculation results for 0.2 and 0.3 m/s. This noise is attributed to the very small change in roll due to the low applied motor torque, resulting a roll value which remains very close to zero. Since the righting moment is dependant on the inverse of $\sin(\phi)$, a value of the roll ϕ close to zero causes unstable values.

IV. CONCLUSION

The horizontal flight stability of the hybrid glider has been examined. The depth controller parameters were tuned using experimental test in a fresh water test tank. Using the tuned depth controller parameters, horizontal flight tests were performed with the auxiliary propulsion module. These tests show the ability of the hybrid glider to fly at a desired depth in a straight line on the horizontal plane. The roll of the glider due to the applied torque is also characterised. The length of the NRC-IOT's Ocean Engineering Basin (OEB) (L: 70 m, W: 35 m, D: 3 m) testing tank did not allow for a conclusive demonstration of the controllability and stability of the controllers used. The OEB tests show that glider is capable of driving at depth by tuning the glider's existing control parameters and no large instabilities are present.

The testing of the horizontal flight mode of a hybrid glider is ongoing. Sea trials with the vehicle have just past tuning the depth controller for salt water and an initial horizontal flight has been performed over a distance of 300 m. Additional future work will involve updating the ded-reckoning navigation algorithm to include horizontal flight modes. Further on, the

integration of a purpose built navigation system for the hybrid glider is planned.

ACKNOWLEDGMENT

The authors would like to thank Paul Winger, George Legge and Tara Perry from the Marine Institute, Jack Foley and Craig Mitchell from Memorial University of Newfoundland (MUN), Jeswin Jeyasuyra and Moqin He of the National Research Council Canada, Paul Lacroix and the Canadian Centre for Ocean Gliders for use of the glider and the Physical Oceanography Department at MUN for providing additional instrumentation and experimental support. This project is supported through funding provided by Natural Sciences and Engineering Research Council, Memorial University of Newfoundland and Suncor-Petro Canada.

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