Swimming Performance of a Hybrid Unmanned Air-Underwater Vehicle

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Abstract—An unmanned vehicle has been developed for high-speed aerial ingress to a target shallow water environment after which it transitions to underwater low-speed operations. This paper describes the computational analysis and experimental results for the final phase of vehicle operations, underwater swimming. Building on previous research, the vehicle employs a unique bio-inspired propulsion and control system for underwater operations. Computational fluid dynamics (CFD) simulation results estimate hydrodynamic characteristics, and experimental data demonstrate swimming performance for two versions of the vehicle. Results and analysis validate the underwater operational capabilities of a hybrid vehicle designed for long-range flight and low-speed swimming.

Keywords—bio-inspired robotics; air-deployed UUV; pectoral fin; underwater propulsion; computational fluid dynamics

I. INTRODUCTION

Research in underwater vehicle technologies is leading to smaller and more maneuverable unmanned platforms that are expanding the envelope of operations into more dangerous and complicated environments. Underwater applications ranging from inspection to sensor network placement and reconfiguration to reconnaissance all benefit from advances in unmanned underwater vehicles (UUVs), and one area that has gained a lot of traction is using biology as inspiration in the design of UUV propulsion and control surfaces.

Several researchers have developed and adapted artificial pectoral fins onto UUVs due to their potential propulsion and control benefits in underwater environments where precise positioning is needed in the presence of changing currents and under waves. These fins have included rigid and passively deforming fins [1][2][3][4] as well as some actively controlled curvature fins [5][6][7].

While this research has revealed a better understanding of thrust producing mechanisms in fish, and led to the development of novel vehicle prototypes that demonstrate amazing maneuvering characteristics, the larger picture of operational use and deployment of these systems needs to be addressed. One major issue is that many of these systems are being developed for operations over relatively short ranges and durations. However, the areas where some of the benefits of these systems are needed include remote or denied environments for which long range, quick ingress would be required. To address this need for a class of UUVs with artificial pectorals fins, a controlled air glide capability was devised to create an unmanned hybrid air-underwater vehicle called Flimmer (Flying-Swimmer) [8].

Building on the research to develop and test the air glide and landing capabilities for Flimmer, this paper presents results of the underwater testing and compares the swimming performance of a swimming-only version of Flimmer, called Flimmer-S, (with no wings) and the full version of Flimmer (with wings). Complementary studies are carried out using computational fluid dynamics (CFD) tools and experimental trials. Previous studies identified a design for a larger vehicle hull to carry a greater payload and allow for larger fins than the WANDA-1 [9], and the geometry of Flimmer builds on this larger WANDA-3 design with the addition of larger fins and a 1.7m span wing. For the underwater swimming studies presented here, it is assumed that this wing is retracted or shed upon transitioning from flying to swimming.

II. DESIGN AND SETUP

The design of the Flimmer vehicle built off previous studies. A number of changes to the underwater propulsion generating fins were required to achieve desired thrust generation and survivability for the mission [5][10]. The result of this redesign process [8] led to a larger fin constructed of more robust materials (Figure 1). Additionally, the Flimmer fins incorporate chordwise flexibility through the use of spring-loaded hinges at the base of the ribs, which provide fore-aft
motion maintaining the tension between segments of the membrane. This design change was essential for maintaining a desired surface shape in between ribs, while also allowing for the large surface curvature changes needed to produce thrust underwater.

In addition to the fin changes, the design of a vehicle hull for the WANDA-3 UUV [9] had to be modified for the long-range flight requirements of the Flimmer vehicle. To achieve this, a wing of 1.7 m span was built through the hull, or fuselage, of the vehicle and the aft mounted fins were moved to the wing tips (Figure 2a). For this first prototype, it was decided to design a fixed-wing vehicle whose geometry remains constant throughout the mission profile. However, the ultimate goal is to achieve a wing that can be retracted or shed upon landing and water entry as this should lead to an improvement in swimming performance, and so a swimming-only Flimmer-S vehicle was also built (Figure 2b). Overall, the mass of the vehicle is 7.6 kg, with a fuselage/hull length of 1.1 m.

The CFD tool employed in this study is governed by the incompressible Navier-Stokes equations in Arbitrary Lagrangian-Eulerian formulation [11]. The present time-accurate flow solver is discretized in space using a Galerkin procedure with linear tetrahedral elements, and has been used and validated for other flow problems in 2-D and 3-D, laminar and turbulent, and steady and unsteady conditions [12][13].

Experiments are conducted in a 45' long by 25' wide by 5' deep pool filled with municipal water. Among other instrumentation, the pool is outfitted with a 12-camera underwater motion capture system manufactured by Qualisys AB. When properly calibrated, this system allows for precise and accurate measurement of vehicle position and orientation through tracking of light-reflective markers positioned on the vehicle (Figure 3).

III. SWIMMING PERFORMANCE

Following long-range air ingress and water landing, the final performance objective for the Flimmer vehicle is to achieve sufficient control over the thrust of the flapping fins to perform low-speed maneuvers underwater. Previous studies of isolated fins flapping in stagnant water \((U_\infty = 0)\) demonstrated that the Flimmer fin produced greater thrust than earlier generations. However, because the Flimmer fin is operating at lower stroke frequencies (0.2-0.8 Hz) than the first and second generation fins (1.0-4.0 Hz) – this is due to torque and speed limits of the actuators – a larger decline in thrust production as a function of flow speed is expected, which is consistent with both previous vehicle and fish studies [14][15][16]. Computational results for the second generation fin flapping at 1.8 Hz showed a 60% decrease in thrust production as \(U_\infty\) increased from zero to two knots [17]. For the same change in flow speed, the Flimmer fin flapping at 0.65 Hz demonstrates a 90% decrease in thrust, and at 0.35 Hz and 0.80 Hz forward thrust is completely eliminated (Figure 4).

Even though we have used computations to design a vehicle hull that has very low drag [9], this large drop in fin thrust as speed increases limits the speed capability for the Flimmer-S vehicle. Comparison of thrust from four Flimmer

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**Fig. 1.** Flimmer fin geometry compared with previous actively controlled-curvature fins developed at the Naval Research Laboratory.

**Fig. 2.** (a) Flimmer prototype showing the fixed wing and four fins (two wing mounted, and two fore body mounted), and (b) swimming-only Flimmer-S prototype showing 4-fin tandem configuration.
fins with the vehicle drag using the computational solver predicts that the Flimmer-S can achieve a terminal speed of 0.66 m/s (1.3 knots) when the fins are flapping at 0.8 Hz (Figure 4) [18].

Measurement of Flimmer-S speed in experiments demonstrates a steady-state forward speed of 0.60-0.70 m/s (1.2-1.4 knots) as shown in Figure 5. This value is in the range of what computations predict, within 8%. Considering the many differences between the computational model and the experimental conditions, including changes in fin kinematics and nonlinearities or asymmetries in vehicle motion – including pitch and heave variation due to flapping and presence of a non-zero sideslip angle – this good comparison between computations and experiments demonstrates a robustness to various unmodeled factors.

For the Flimmer vehicle with wings, measured steady-state forward speed is 0.34 m/s (0.68 knots), which is 46% lower than for the Flimmer-S – and it also takes Flimmer longer to reach its top speed from rest (about 7 seconds, up from 4 seconds for Flimmer-S) due to the inertia of the wing. This 0.34 m/s speed is also 42% lower that the CFD prediction of 0.59 m/s (1.15 knots). This discrepancy with computations is made even more significant because of the good agreement between CFD and experiments for the Flimmer-S vehicle.

One explanation for the difference between computations and experiments for the Flimmer vehicle can be seen in the variation in drag with swimming angle of attack, $\alpha_v$, as shown in Figure 6a for a vehicle speed of 0.51 m/s (1 knot). For the Flimmer-S vehicle, small changes in angle of attack only have small effects on vehicle drag due to the relatively compact and streamlined hull design. In contrast, the large wing of the Flimmer vehicle demonstrates much larger increase in drag as the angle of attack is varied from the optimal $\alpha_v = 2^\circ$. In experiments, the forward speed measurements of the Flimmer vehicle were taken at $\alpha_v = -5^\circ$ (Figure 6b). This slightly nose down orientation to the flow increases the drag by 180%, and this additional drag brings the computed maximum Flimmer speed down to 0.46 m/s (0.92 knots) (Figure 7).

Another explanation for the difference is from changes in the fin membrane during testing. In testing the Flimmer, more so than testing the Flimmer-S, the fin membranes were prone to being pulled down the ribs, leading to a smaller fin surface area. Additionally, on the Flimmer vehicle the trailing edge of the forward mounted fins was cropped slightly to avoid collision with the leading edge of the wing. To compensate for this in models of fin thrust, $T$, we scaled the thrust by the fin area and effective speed as defined by,

$$T = \frac{1}{2} \rho_w V_{\text{eff}}^2 A_f C_T$$

$$V_{\text{eff}} = \sqrt{V^2 + V_{cp}^2}$$

where $A_f$ is the fin surface area, $\rho_w$ is the density of water, and $V_{cp}$ is the mean velocity of the fin at the center of pressure during the flapping cycle. Compensating for a change of approximately 30% reduced fin span and 50% reduced fin area, in addition to the effects of varying angle of attack, our models predict a vehicle speed of 0.33 m/s (0.66 knots) (Figure 7). Accounting for these differences, the CFD and experimental results for Flimmer forward speed compare well.
Experimental measurements of heading angle and rate of change during a turn-in-place yaw maneuver were also performed (Figure 8). By changing the curvature of the left- and right-side fins, a differential in thrust is achieved – one side producing forward thrust and the other side producing reverse thrust [5]. An open-loop yaw maneuver was achieved by running the left-side fins with 50% forward gait curvature and the right-side fins with 100% reverse gait curvature. This combination of gaits results in zero net forward thrust for the vehicle due to the asymmetry of the fin, and thus a turn-in-place maneuver.

Results demonstrate a 34°/s maximum yaw rate for the Flimmer-S vehicle and a 17°/s maximum yaw rate for the Flimmer vehicle. This 50% reduction in maximum yaw rate demonstrates the effects of the large wing on rotational drag. Even though the fins are positioned at the wing tips, providing additional control authority over the yaw moment, the drag effects of the wing outweigh this. However, Flimmer does reach its terminal heading rate of change faster than Flimmer-S, which could also be due in part to the rear fins placed at the wing tips creating a larger moment to overcome inertia.

IV. DISCUSSION AND CONCLUSIONS

To evaluate the swimming performance of a hybrid air-underwater vehicle, both CFD and experimental studies were performed on a wingless vehicle and the full winged vehicle. After considering and accounting for differences between the computational model and the actual Flimmer-S and Flimmer prototypes, the experimental results demonstrated agreement with predicted performance.

Underwater, the thrust production of the Flimmer fin was evaluated over a range of swimming speeds. Combined with the drag of the vehicles and changes to the fin membrane during testing, computations showed a 0.66 m/s speed capability for Flimmer-S and a 0.34 m/s speed capability for Flimmer. By demonstrating agreement with experimental results, the computations also showed the effects of the shifting fin membrane and swimming angle of attack. For Flimmer, where the wing diminishes speed and turning performance, making necessary changes to the vehicle mass properties and fin membrane attachment to the ribs, vehicle speed performance should be greatly improved. And in a final
version of Flimmer, where the wing could be shed or retracted on landing, the results of the Flimmer-S vehicle demonstrate potential improvement in underwater maneuvering performance.

Overall, achieving swimming of the Flimmer vehicle demonstrates the final stage of hybrid vehicle operations. Flight, landing, and swimming have now been tested, and the performance has been characterized. The swimming results of Flimmer and comparison of these results with Flimmer-S demonstrate the effects of a winged platform on low-speed underwater operations. Future versions of the Flimmer vehicle will consider other configurations to improve swimming performance. The final vehicle platform using bio-inspired thrust control surfaces will enable missions in near-shore areas where hover capability in the presence of changing currents and under waves is desired, and will also provide the long range ingress capability needed to emplace such a vehicle in remote or denied areas.

REFERENCES


