Design of a Flapping Foil Underwater Vehicle

Stephen Licht, Franz Hover and Michael S. Triantafyllou
Department of Ocean Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139 USA
Email: slicht@mit.edu

***Abstract*— The design, construction and testing of a biomimetic flapping foil autonomous underwater vehicle is detailed. The project is a proof of concept for the use of flapping foils as the sole source of propulsion for an underwater vehicle. We intend to use the vehicle in several physical arrangements to compare the swimming performance of different shapes and foil arrangements.**

The vehicle was designed for maximum flexibility and scalability in terms of the number and placement of foils through the creation of self-contained modular actuators, each requiring only DC power and a connection to the vehicle Ethernet LAN.

The current vehicle implementation consists of four actuators, each driving a single foil with a span of 0.40m and an average chord of 0.10m. The foils are paired port-starboard, with one pair at the bow and one at the stern. Each foil has a 180 degree range of motion about the roll (chordwise) axis and unrestricted motion about the pitch (spanwise) axis. The dimensions of the vehicle without the foils is approximately 2m x 0.5m x 0.5m.

Results from disparate sets of tests have been gathered to demonstrate the suitability of flapping foils for the generation of thrust and force vectoring during cruising, of thrust at zero-speed, and the development of rapid transient forces with a single foil stroke. All of these are requirements for operation in dynamic environments which impose unpredictable transient forces on an underwater vehicle.

I. INTRODUCTION

The study of the kinematics and hydrodynamics of animal swimming has long shown that the performance of man-made underwater vehicles is severely lacking in terms of efficiency and maneuverability.

The state of the art in AUV technology is represented by highly streamlined body shapes driven by propellers, stabilized and controlled with lifting surfaces. Standard operations with AUVs consist primarily of traversing back and forth over a survey area at speeds just high enough to maintain headway and to compensate for prevalent currents. These vehicles are not well equipped for operations which require position control at zero velocity, or rejection of large transient disturbances.

By exploiting the hydrodynamics of fishlike swimming, we hold out hope for a vehicle which adds the ability to maneuver in dynamic environments without sacrificing efficiency in cruising from station to station. Such a vehicle could expand the application of AUVs to new scientific, commercial and military endeavors.

Extensive testing of oscillating foils, which mimic a common mode of animal swimming, has been performed in the MIT Ship Model Testing Tank [1], [2], [3]. The result is a solid understanding of the fundamental parameters of thrust production in foils. The flapping foil vehicle represents our first attempt to put this knowledge into practice on a vehicle scaled to support a significant scientific payload.

II. DESIGN GOALS

The vehicle is intended to reach a top speed of 2m/s when enclosed in a streamlined fairing, and to have sufficient maneuvering authority to independently control position in pitch, heave, surge and sway in a dynamic environment.

The starting point for the design was a vehicle sized no greater than 2m x 0.5m x 0.5m, for ease of deployment, with four foils placed so as to take advantage of port-starboard and top-bottom symmetry. However, our primary objectives also include flexibility in terms of the vehicle size and shape, and the freedom to adjust both the number and the placement of the foils without incurring major design changes.

The vehicle is intended for autonomous operation, although tethered operation is possible. Untethered operation eliminates concerns about fouling the foils during maneuvering. As a result, pre-programmed mission following, independent error handing, an onboard power source, and data storage capability were all required.

Design for shallow water operation was pursued, since greater depth rating adds cost and complexity with no corresponding increase in experimental functionality. In addition, since tests will initially be performed only in confined water, inertial sensors will be our primary source of navigation data. We anticipate that minimal long term tracking accuracy will required for short, supervised missions focused on local control issues.

III. FOIL ACTUATORS

Most of the design effort was concentrated on the distinguishing characteristic of the vehicle, the foil actuation. A key requirement for the vehicle is scalability and flexibility in terms of both the number of foils, and their positions and orientations. To meet the flexibility requirement, each foil actuator was conceived as part of a waterproof module that could be mounted anywhere on the vehicle frame. In addition, each module can be operated entirely independently from the other foils. To allow for scalability, the modules are designed such that as more modules are added to the vehicle, there is no complexity added to the power and communication circuits.

A single foil module contains all the components necessary to add another foil to the vehicle. Each module contains a

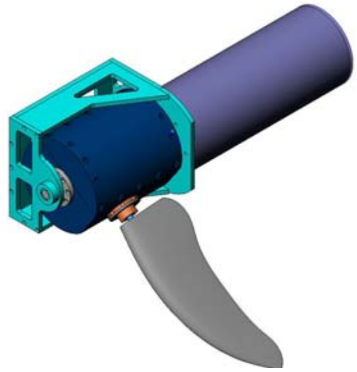


Fig. 1. Foil Actuator Module

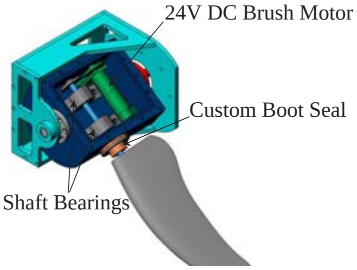


Fig. 2. Detail of Foil Actuator Module

196W and a 15W DC brush motor with optical encoders (Litton-Polyscientific, Blacksburg, VA) which actuate foil roll and pitch, respectively. The corresponding motor control circuit is also housed in the module, with an Ethernet enabled two-axis motion control card, and two PWM amplifiers. The addition of a new module entails only two connections: an Ethernet line to a central hub on the vehicle LAN, and a fused connection to the power bus. Since the hub acts in some sense like a bus connection, no additional wiring is required.

The housing for the module is shown in Figure 1. The larger cylinder shown remains stationary with respect to the vehicle while the second, smaller, cylinder rotates about its axis with respect to the larger. The stationary cylinder, machined from 6.5” schedule 80 PVC, contains the larger of the two DC brush motors, as well as the motion control card and the amplifiers for both motors. The smaller cylinder splits into two semi-cylindrical pieces, with an interior cavity machined out of solid Delrin rod. An open view of the pitch cylinder is shown in Figure 2. The full range of motion on the roll axis is $180°$, while the pitch motion is completely unrestricted. The two shaft seals consist of rotary o-ring seals embedded in a custom molded flexible urethane boot.

In order to maximize the reliability, and hence the usefulness of the vehicle as a platform for different research teams, an emphasis was placed on simplicity and robustness of the actuators. One result is that mass of the solid moving parts in the dual housing design is relatively high, increasing the energy wasted on overcoming the rotational inertia, and potentially decreasing the bandwidth for thrust vectoring. We anticipate that future designs can be made substantially smaller and lighter, once testing and long term operation reveal areas of over- and under-design. The addition of properly tuned springs would realize substantial power savings. In addition, once minimizing module size becomes a priority, e.g. with the need for payload space and reduced power operation, the cost of smaller components will become justified.

IV. ELECTRICAL SYSTEMS AND COMMUNICATION

The power system is run at 24V DC which is supplied by a pair of SLA gel secondary cells connected in series. Actuator power cut-off, processor reset and power cycling, and total vehicle power kill switches are activated with magnetic proximity switches.

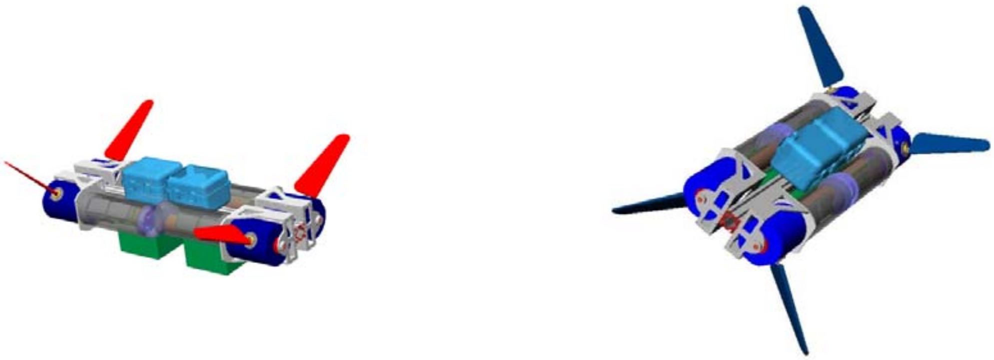
The central processor is an Octagon Systems Pentium III single-board computer running RedHat Linux v7.3, while each actuator module contains a Galil 1425 2-axis motion control processor. A Crossbow 6-axis accelerometer is used for navigation, with data collection performed by a 16 channel/12 bit 330KHz A/D converter from Eagle Technology.

Each of the separate housings that comprise the vehicle are connected to an Ethernet LAN with a star-shaped topology centered on a housing containing a wireless access point and hub. The appeal of Ethernet lies in both high communication rates and the ease with which new components can be connected. The Galil motion control cards were chosen in part for their compatibility with Ethernet communication, power distribution is controlled entirely through commands to an embedded server with digital I/O capabilities (a Hello!Device 1100 from Sena Technologies.) One result of the system architecture is that any computer running a web browser, and the OEM supplied software for the motion control card, can route power to one or more foil modules and control the foil motion directly. Communication with the vehicle will only be possible while the vehicle is at the surface.

The traditional argument against using Ethernet in control applications is that it is not structured to deliver information at deterministic times, but this is not a concern here. The microsecond timing required for the foil to accurately follow a predetermined motion path is dealt with at the actuator level in the motion control card, which is directly connected to the motor encoders. The higher level commands from the central processor must update only on the order of a fraction of the foil oscillation period. The extremely low probability of packet delays over 10ms on a small quiet local area network, or LAN, is inconsequential in comparison to a minimum foil motion period on the order of 0.5-1.0s.

V. VEHICLE LAYOUT

The vehicle is initially be arranged with two pairs of foils placed port-starboard along the median line, at bow and



(a)

(b)

Fig. 3. Two Views of Fore-Aft Paired Fin Layout

stern, as drawn in two views in Figure 3. This configuration additionally results in fore-aft symmetry. (The most likely second option will shift one pair of the foils 90° about the vehicle primary axis, so that they are oriented up-down, a configuration not unlike that adopted by the boxfish.)

The primary advantage of maximizing symmetries is the resulting simplification of the control problem . The motion of the foils can be properly phased with respect to one another so as to cancel the unwanted cyclic forces that oscillating foils generally produce perpendicular to the desire impulse.

In the initial configuration , the maximum dimensions without foils is 2m x 0.5m x 0.5m, while the foils protrude 0.4m from each side, with 0.1m average chord. All foils have a 180° range of motion in roll, and unrestricted motion in pitch. The actuators are mounted to an aluminum spine which measures 5cm x 10cm with a rectangular cross section. All other vehicle components, including battery and electronics housings and foam for buoyancy are mounted directly to the same spine.

VI. DESCRIPTION OF FOIL FLAPPING KINEMATICS

The large displacement flapping motion of the wing is referred to as the roll motion. The twisting or feathering of the wing is referred to as the pitch motion. The basic motion tested involved sinusoidal roll and pitch motions, referred to here as 'simple harmonic' foil kinematics.

The roll position of the foil through time during simple harmonic motion is defined as,

$$\phi(t) = \phi_0 \sin(\omega t) + \phi_{bias} \tag{1}$$

where ϕ_0 is the roll amplitude in radians and ω is the frequency of the foil motion in radians per second. ϕ_{bias} is a static roll bias used to change the mean roll position of the foil. For the purpose of testing with a single foil, ϕ_{bias} is arbitrary, but when multiple foils are in use on a vehicle, the absolute and relative values of ϕ_{bias} for the different foils comes into play as part of any control strategy.

The pitch position of the foil through time during simple harmonic motion is defined as,

$$\theta(t) = \theta_0 \sin(\omega t + \psi) + \theta_{bias} \tag{2}$$

where θ_0 is the pitch amplitude in radians and ψ is the phase angle between pitch and roll in radians. θ_{bias} is a static pitch bias used for maneuvering. The phase angle, ψ, for all experiments described herein, is $\frac{\pi}{2}$ and we can therefore write $\theta(t)$ as,

$$\theta(t) = \theta_0 \cos(\omega t) + \theta_{bias} \tag{3}$$

For heaving and pitching foils, the motion is non-dimensionalized using three parameters: Strouhal number (St), maximum angle of attack (α_{max}), and heave amplitude to chord ratio. The corresponding parameters in rolling and pitching motion for a flapping foil are the St and α_{max} as calculated at a location 70% of the distance from the root of the foil to the tip. The distance to this point from the axis of roll rotation is denoted by $r_{0.7}$. (Note that $r_{0.7} \geq 0.7s$ where s is the span of the foil.) The ratio of the arc length at $r_{0.7}$ to the chord, denoted as $\frac{h_{0.7}}{c}$ replaces the heave amplitude to chord ratio from the two-dimensional case.

For three dimensional kinematics we can express the angle of attack at $r_{0.7}$ as,

$$\alpha(t) = -\arctan\left(\frac{\omega r_{0.7}\phi_0 \cos(\omega t)}{U}\right) + \theta_0 \cos(\omega t) + \theta_{bias} \tag{4}$$

For three dimensional kinematics, the Strouhal number is defined,

$$St = \frac{2 r_{0.7} \phi_0 f}{U} \tag{5}$$

The Strouhal number can be thought of as a measure of the aggressiveness of the flapping motion with respect to the incoming flow speed. Maintaining the same St while increasing the flow speed requires an increase in flapping

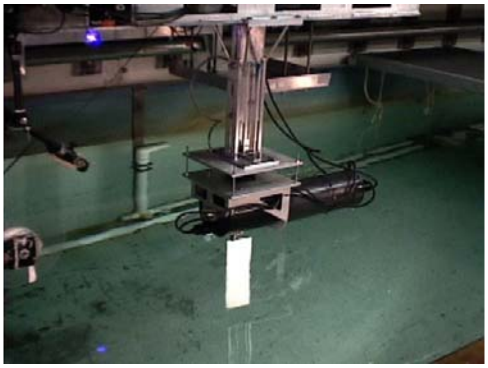


Fig. 4. Foil Actuator Testing Apparatus

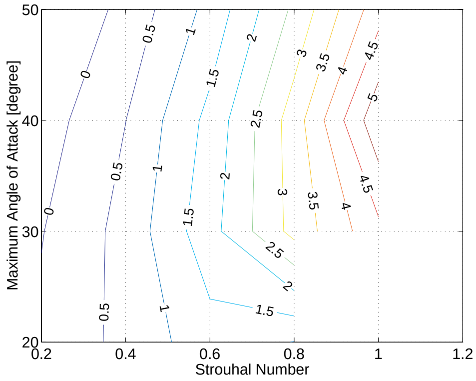


Fig. 5. Contours of Thrust Coefficient for Cruising Operation

frequency, amplitude or both. The factor of two results in scaling as a function of approximate wake width, which emphasizes the relationship between St and vortex shedding patterns in the foil wake.

VII. MANEUVERING TECHNIQUES

We designed the flapping foil vehicle for operation in dynamic environments. In order for an underwater vehicle to operate near obstacles in unsteady flows, it must be able to generate large forces rapidly and reliably during both hovering and cruising. A variety of experiments performed in the MIT Ship Model Testing Tank and at the MIT Marine Hydrodynamics Laboratory over the last several years have

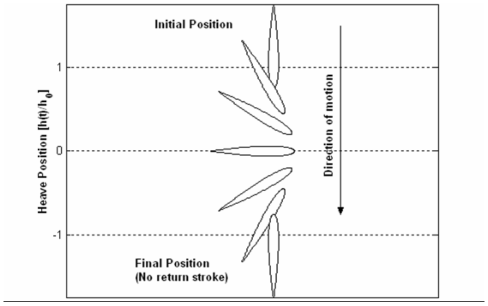


Fig. 6. Example of Single Stroke Motion

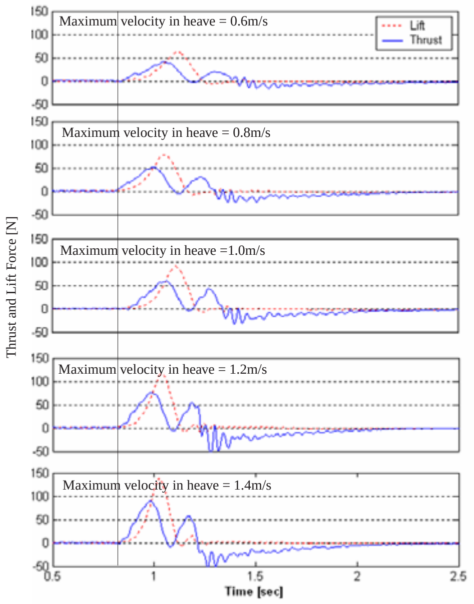


Fig. 7. Forces Produced by Single Stroke

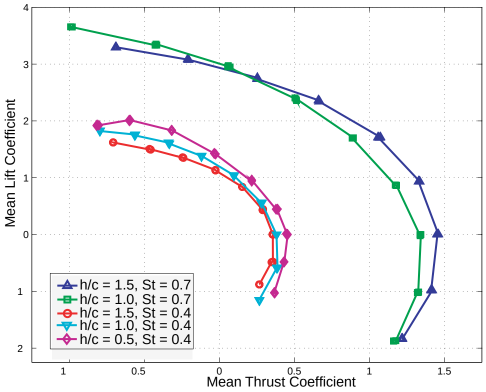


Fig. 8. Lift Produced by Pitch Bias Maneuvering

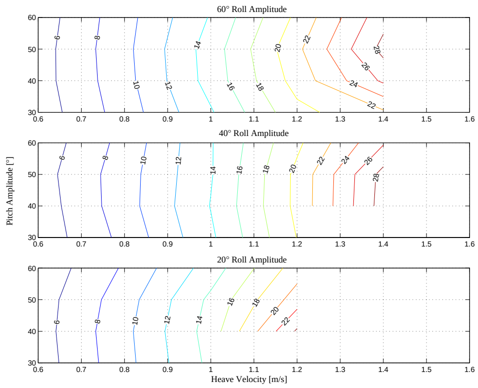


Fig. 9. Contours of Thrust for Sinusoidal Stroke at Zero-Speed [Newtons]

demonstrated the promise of flapping foils in this regard.

Before the development of the rolling and pitching foil actuator for this vehicle, attention was focused primarily on heaving and pitching foils operating in two-dimensional flow [2] [3]. With the advent of the rolling and pitching actuator, contours of foil thrust have been mapped for the three dimensional case as well [5]. Figure 5 shows thrust developed as a function of St and maximum angle of attack for a foil with a roll amplitude of $40°$. All data was acquired in a towing tank, using the apparatus shown in Figure 4, which consists of one of the vehicle actuators mounted to a dynamometer on an overhead carriage. Thrust is normalized by $\frac{1}{2}\rho U^2 A_{foil}$, where ρ represents fluid density, U is the towing velocity of 0.5m/s, and A_{foil} is the projected foil area.

At a high maximum angle of attack, thrust increases with increasing Strouhal number, as expected. However, at low angles of attack increasing the aggressiveness of the stroke by increasing either frequency or amplitude does not necessarily result in higher thrust coefficients, indicating that some care must be taken in choosing appropriate kinematics. Based on these results, the top forward velocity of the vehicle has been estimated at between 0.5m/s given a drag coefficient of 1, and as high as 2 m/s given a drag coefficient of 0.2 [6]. Qualitatively similar results have been been obtained for two-dimensional foils, as seen in [2] [3], and indicate that optimization of the swimming stroke can lead to gains in both efficiency and authority of as much as 25 to 30 percent. No attempt has yet been made to further optimize the three dimensional swimming stroke.

Strouhal number and angle of attack are effective predictors of foil thrust for foil Reynolds numbers over 40,000 [3]. However, at zero-speed the Strouhal number is driven to infinity since the term is normalized by velocity. A distinction is therefore made between cruising and hovering modes, with cruising corresponding to vehicle speeds above approximately 0.4m/s and hovering referring to near zero-speed operation. Below 0.4m/s, comparisons based solely on the Strouhal number are not sufficient, as there there is a significant Reynold's number dependence as well.

Data has also been gathered for both average and instantaneous thrust development for foils at zero-speed using the same apparatus. Figure 9 shows contours of thrust in Newtons at zero-speed using a 0.4m x 0.1m foil using the simple sinusoidal motion described above. Roll amplitudes of $20°$, $40°$ and $60°$ were tested, with the maximum velocity of the foil at the 0.7 span point ranging from 0.6 to 1.2m/s. The figure demonstrates that the primary parameter in determining thrust development in hovering is the maximum angular velocity of the foil during the stroke. Increasing the roll amplitude increases the maximum velocity that this actuator is capable of, and there is preferred maximum pitch amplitude which varies from around $30°$ to $50°$ as a function of the roll amplitude. Based on these tests, the four foils of the current design, operating in concert, can together deliver at least 120 Newtons of average force at zero speed. By appropriately phasing the motions of the four foils, we should be able to compensate for the oscillatory nature of the forces generated to reject steady disturbances.

Properly used foils should be able to generate the forces need to reject large, unpredictable transient forces. A series of tests with different single strokes used for starting from rest, performed by [3] with foils in two-dimensional flow, has shown that foils are capable of rapidly producing vectored impulses given the correct kinematics. Figure 6 gives an example of a possible single stroke. Time traces of thrust produced for various maximum foil velocities, using this stroke template, are shown in Figure 7. Note that the timescale of the impulses generated, as measure by rise time, is on the order of 0.1-0.2 seconds, with maximum forces well over 100 Newtons produced by a 0.60m x .10m foil, indicating that rapid responses to disturbances are possible.

Finally, a simple method for generating maneuvering forces during cruising, i.e. force perpendicular to the direction of motion, has been demonstrated with both two-dimensional and three-dimensional foils [4]. Figure 8 plots mean force vectors that can be generated simply by adding a constant bias to the pitch motion while executing the simple sinusoidal swimming motion. This ‘pitch bias’ corresponds to a non-zero value of θ_{bias} in equation 3. The two distinct sets of curves correspond to Strouhal numbers of 0.4 and 0.7, with roll amplitudes of 0.5, 1.0 and 1.5 chords. Insensitivity to roll amplitude is illustrated by the close grouping of the two sets of curves. All tests were performed with a maximum angle of attack of $15°$. The shape of the curves around the zero bias point indicates that for small bias angles (less than $5°$) significant lift can be developed with relatively slight drop in thrust. The weak coupling between thrust and lift generation for small pitch bias should allow for decoupling of speed and pitch control in a vehicle being controlled to constant forward speed. In the fore-aft paired fin configuration, there is the option to use either one or both pairs of foils in concert to generate pitch moments. In the boxfish orientation, yaw can also be actuated by using pitch bias on the up-down oriented fins.

VIII. CONCLUSION

This paper presents the design of an underwater vehicle which can be used as an experimental platform for propulsion and maneuvering using biologically inspired flapping foils.

Results are presented indicating that high thrust can be produced by foils using sinusoidal motions with well chosen parameters (amplitude, phase, and frequency) both during cruising operation ($> 0.4m/s$) and hovering (at or near zero-speed.) In addition, force vectoring using pitch-biasing, and rapid generation of transient forces with single foil strokes has been demonstrated.

The challenge ahead is to synthesize this body of knowledge to provide effective maneuvering strategies for the vehicle. Future work will involve quantifying the most effective manner of transitioning from hovering to cruising and vice versa, determining the most effective foil positions for disturbance rejection in different scenarios, and identifying and taking advantage of fluid interactions between foils mounted in close proximity on a single vehicle.

ACKNOWLEDGMENT

Support is acknowledged by the Sea Grant College Program under Grant NA16RG2255, and the National Defense Science and Engineering Graduate Fellowship Program.

REFERENCES

[1] J. Anderson, “Vorticity control for efficient propulsion,” PhD Thesis in Oceanographic Engineering, Massachusetts Institute of Technology, MA, February 1996.

[2] D. Read, “Oscillating foils for propulsion and maneuvering of ships and underwater vehicles,” Master of Science in Naval Architecture and Marine Engineering, Massachusetts Institute of Technology, MA, February 1999.

[3] O. Haugsdal, “Motion control of oscillating foils for steady propulsion and starting maneuvers,” Master’s Thesis, Massachusetts Institute of Technology, MA, 2000.

[4] M. Flores, “Flapping motion of a three dimensional foil for propulsion and maneuvering of underwater vehicles,” Master of Science in Ocean Engineering, Massachusetts Institute of Technology, MA, May 2003.

[5] V. Polidoro, “Flapping foil propulsion for cruising and hovering autonomous underwater vehicles,” Master of Science in Ocean Engineering, Massachusetts Institute of Technology, MA, May 2003.

[6] S. Licht, V. Polidoro, M. Flores, F. Hover, M. Triantafyllou, “Design and Projected Performance of a Flapping Foil AUV,” in *Proceedings of the International Symposium on Unmanned Untethered Submersibles Technology (UUST)*, Durham, NH, August, 2003.