CFD based Analysis and Design of Biomimetic Flexible Propulsors for Autonomous Underwater Vehicles

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I.   Introduction

This work is part of a research program designed to develop a maneuvering propulsor for an Autonomous Underwater Vehicle (AUV's) based on the mechanical design and performance of fish fin. Fish are notable for their ability to maneuver and to accurately position themselves even in highly unsteady flows. Fish can maneuver in tight spaces and accelerate and decelerate quickly from rest or low speed with the same propulsion system. Also, fish fins are remarkable fluid control devices with supporting bony elements that are under active muscular control. In addition to muscular actuation at the base of the fin which governs overall fin position, fish fins possess a bilaminar design that allows active control of propulsor surface curvature (Lauder et al., 2005). This paper will focus on hydrodynamic analyses of bluegill sunfish's pectoral fin which were carried out to guide the design of a flexible propulsor for AUV's.

II.   Bio-inspired Flexible Propulsor Design Approach

We have taken a six pronged approach to the analysis and design of a flexible propulsor based on principles derived from the study of fish fin function (Lauder et al., 2005). First, we have undertaken a detailed investigation of 3D kinematic patterns exhibited by fish fins during locomotion. Second, we have measured the mechanical properties of the fin rays and membrane that comprise the propulsive surface. Third, we have studied the hydrodynamics of the fin function of freely swimming fishes using digital particle image velocimetry (DPIV). Fourth, a computational fluid dynamic (CFD) study of fish fin function has been done that allows calculation of fin flow patterns using actual 3D fish fin kinematics. Fifth, a detailed study of the low dimensional models of the pectoral fin kinematics and associated hydrodynamics has been carried out to incorporate the fish fin motion into the engineered fin. Sixth, biomimetic, physical, robotic models of the fin have been developed that can reproduce the complex fin motions that fishes use for propulsion and maneuvering.

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A first generation, functional, prototype of the bio-robotic fin was produced by the Bioinstrumentation Laboratory at MIT (Tangorra et al., 2007). The architecture of the first generation of the bio-robotic pectoral fin called as "flex fin" was inspired by the anatomy of the bluegill pectoral fin. Instead of replicating the fish anatomy, it was decided to take advantage of bilaminar fin rays and tendon driven actuation to perform movements similar to the bluegill. On the other hand, in the second generation of bio-robotic fin design, named as "cupping fin", the intention was to replicate Mode-1 movement of the sunfish's fin. Proper Orthogonal Decomposition (POD) analyses of the experimentally observed fin kinematics revealed that Mode-1 represents 37% of the total motion. Mode-1 gait involves considerable movement away from the body where the fin cups forward as it is abducted. It leads to a rapid acceleration of the fin dorsal and ventral edges, forming two leading edges from them. CFD analyses of Mode-1 motion demonstrated that this gait produces 45% of the total thrust during the fin-beat cycle with 73% propulsive efficiency (Bozkurttas, 2007). Computational results also suggested that the effect of the shape of the bluegill's fin should not be underestimated; its asymmetric shape was advantageous to move the fin into a flow, for giving the fin the desired passive flexibility, and for directing thrust along the direction most needed by the fish. Therefore, the basic design for the cupping-fins used five fin rays of lengths proportional to those of the sunfish pectoral fin that were attached to small diameter hinges mounted into a curved, rigid base (Tangorra et al., 2007). In this paper, some of the CFD analyses of the fish fin locomotion which were contributed to the bio-robotic fin design approach are discussed in brief and preliminary performance results from the cupping fin design are presented.

III.   Low dimensional Models of Fish Fin Kinematics and Associated Hydrodynamics

Experimental investigations of the bio-hydrodynamics of swimming animals are limited by their inability to provide full-field, spatially and temporally resolved, velocity and pressure measurements. It is often difficult to control/predict the motion and location of the animals under test conditions, and to instrument the test subjects with sensors to the extent needed without disrupting their natural behavior. For instance, no method currently exists for extracting the surface pressure and shear stress distribution on a structure as delicate as the flapping pectoral fin of a fish (Mittal 2004). Computational modeling overcomes many of these difficulties; however it has its own key challenges which are discussed on detail in Mittal, 2004. We have developed a finite difference based Navier-Stokes solver with immersed boundary methodology to handle complex 3D biological flow problems (Bozkurttas et al., 2005; Bozkurttas et al., 2006; Dong et. al, 2005). The primary feature of the current immersed boundary method is that simulations with complex boundaries can be carried out on stationary non-body conformal Cartesian grids and this eliminates the need for complicated remeshing algorithms for moving boundaries that are usually employed with conventional Lagrangian body-conformal methods. Velocity information of the nodes defining the immersed boundary needs to be provided at each time step of simulations as an input. This way experimentally extracted fin kinematics involving active and passive deformations can be studied without solving the two-way coupled fluid-structure interaction problem.

The motion of the sunfish pectoral fin was recorded while the fish swam at 1 BL/s using two calibrated high-speed video cameras (250 and 500 fps with 1024 *1024 pixels) (Lauder et al., 2005). Twenty equally spaced frames from the video were selected over each fin beat. Points were digitized along each of the 14 fin rays (the bony elements that support the fin membrane) in the two stereo views to give up to 300 points per frame describing the fin surface in three dimensions. Experimental hydrodynamic analyses (Lauder et al., 2005; Lauder et al., 2006) as well as numerical simulations of experimentally extracted fin kinematics (Bozkurttas et al., 2005; Mittal et al., 2006) revealed that bluegill sunfish pectoral fin produces two peaks of thrust during steady forward swimming. Although, this is known, both of these studies do not identify which particular movement produces thrust at which phase of the motion. A clear understanding of motion patterns allows us to specify certain kinematic schemes for bio-robotic fin designed for AUV's.

The kinematics of the pectoral fin during steady forward swimming and the associated hydrodynamics was highly complex which does not lend itself easily to an analysis based on simple notions of pitching/heaving/paddling/rowing kinematics or lift/drag based propulsive mechanisms. A more creative approach is therefore needed for extracting essential features of the pectoral fin kinematics so that they could be recreated in an engineered design. One of the POD techniques, singular value decomposition (SVD) was used in this work to extract essential features of the bluegill's fin kinematics. POD is a powerful and elegant method for data analysis aimed at obtaining low-dimensional approximate descriptions of a high-dimensional process or dataset (Liang et al., 2002). The most remarkable feature

of the POD is its optimality: it provides the most efficient way of capturing the dominant components of any process with only a finite number of modes, and often surprisingly few modes. The POD method has been used in many areas including random variables, image processing, data compression, process identification and oceanography, etc. (Liang et al., 2002). As far as we know, our use of POD for extracting essential features of the pectoral fin kinematics represents a first-of-its-kind effort.

The singular value spectrum for the bluegill's fin kinematics is shown in Figure 1 along with a cumulative plot for the same data. The cumulative values show that the first two, three and five modes capture 55%, 67% and 80% respectively of the total motion and Mode-1 itself represents 37 % of the total motion (Bozkurttas et al., 2006). POD analysis has decomposed the fin kinematics into its orthogonal components and helped us understand the main aspects of bluegill's pectoral fin movements in steady forward swimming. POD results are also beneficial in reconstructing low-dimensional approximations of the full motion using the first N energetic modes. Low-dimensional models of the fin gait are attained by synthesizing Mode-1+2, Mode-1+2+3 and Mode-1+2+3+4+5. Subsequently, CFD simulations of these gaits were carried out and used to define the repertoire of motions that bio-robotic fins be able to perform.
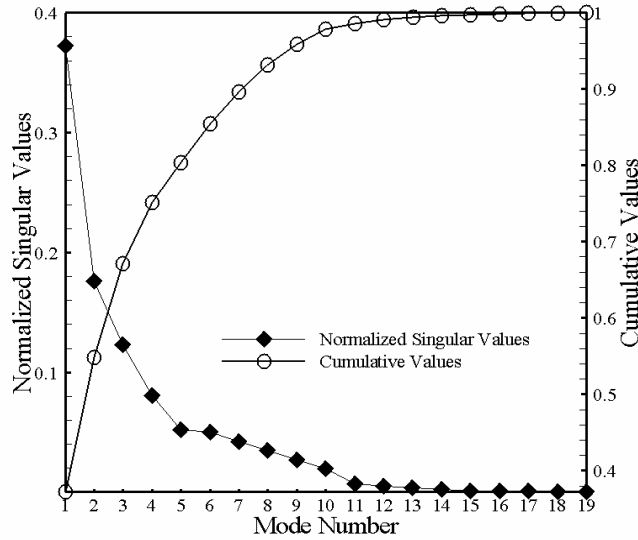

Figure 1. Normalized singular and cumulative values extracted from POD analysis of bluegill sunfish pectoral fin movements during steady forward swimming.

Comprehensive studies have been carried out to assess the effect of the grid resolution and domain size on the salient features of the flow and also to demonstrate the accuracy of the selected grid for the "complete motion" (CFD simulation of experimentally extracted fin kinematics) (Bozkurttas et al., 2006). Analyses of low dimensional models were carried out at experimental flow conditions using the same domain and grid size of the complete motion. The experimental Reynolds number is estimated as 6300 (defined as $\mathrm{Re}_\infty = U_\infty L_S / \nu$, where U_∞, L_S, and ν are the fish forward velocity, spanwise size of the fin and the kinematic viscosity respectively) and Strouhal number (defined as $\mathrm{St} = L_S f / U_\infty$ where f is the flapping frequency) is 0.54. A domain size of $3.8\,L_S \times 4.5\,L_S \times 1.8\,L_S$ is selected and a grid size of 201×193×129 is used for this domain which amounts to 4.9 million grid points.

Comparison of time variation of thrust coefficient between the complete motion and Mode-1 and Mode-1+2+3 gaits are given in Figure 2. Mode-1 captures the first peak of the thrust in the abduction phase (when the fin gets away from the body) with smaller amplitude and the second peak in the adduction phase (when the fin comes back to the body) is almost non-existent. As mentioned before, Mode-1 is the so called "cupping" movement of the fin and it represents 37% of the total fin motion based on the normalized singular values given in POD spectrum (see Figure 1). Time averaged thrust coefficient for Mode-1 case is calculated as $\overline{C_T} = 0.5$ which corresponds to 42% of the thrust amount produced by the complete motion. On the other hand, Mode-1+2+3 gait captures the thrust production of

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complete motion up to ¾ of the cycle. Mean thrust is calculated as $\overline{C_T} = 1.09$ for this gait and this is 8% less than the complete motion. Thus, 67% of the motion captured by the first three modes produces 92% of the complete thrust where the missing part is due to the remaining modes in the POD spectrum. POD essentially filters out the features of the motion that are inconsequential and may have been introduced by experimental error. This clearly suggests the effectiveness and optimality of the POD method.
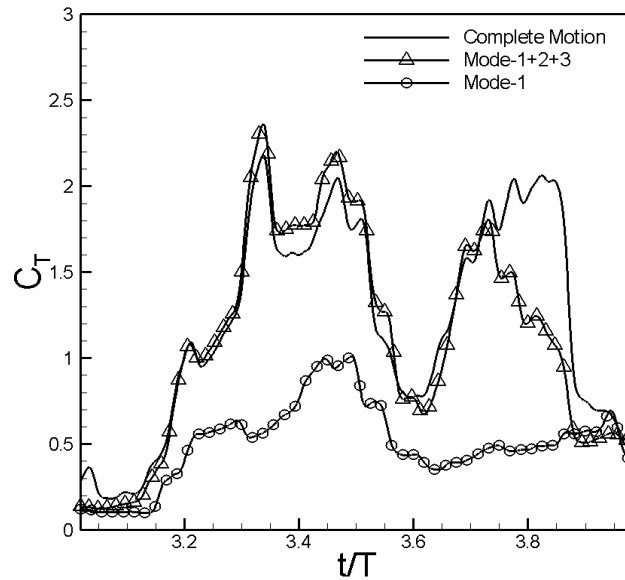
Figure 2. Comparison of time variation of force coefficients between complete motion and POD synthesized gaits at $\mathrm{Re}_\infty = 6300$ and $St = 0.54$.
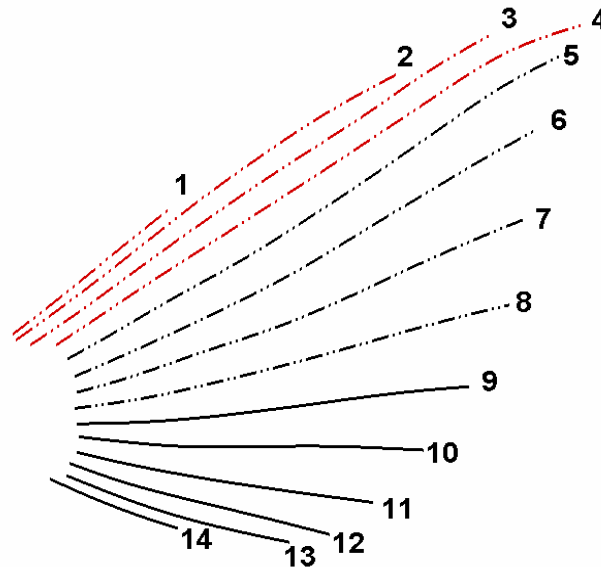

Figure 3. Bluegill's pectoral fin consists of 14 bony rays which form the full planform. Two other planforms interpolated from rays 1-4 and rays 1-8 have also been simulated to investigate their performance.

The importance of the pectoral fin shape in the hydrodynamic performance of the fin was addressed by the results of numerical simulations. Time averaged distribution of the thrust force over the fin surface has shown that dorsal part of the fin produced most of the thrust (Bozkurttas, 2007). The pectoral fin of a bluegill sunfish has 14 bony rays (see Figure 3). In this figure, fin rays are numbered sequentially starting from the dorsal edge (ray-1) to the ventral edge

(ray-14). These rays support an asymmetric planform shape for the pectoral fin of the bluegill sunfish. To further investigate what portion(s) of the fin is (are) responsible for thrust production and to see the effect of removing ventral part of the fin on the flow, two different fin planforms have been interpolated from rays 1-4 and rays 1-8. These planforms have been tested carrying out CFD simulations while the fins undergo POD Mode-1+2+3 gait at $\mathrm{Re}_\infty = 1440$ which is one fourth of the experiments. Strouhal number was kept as 0.54, the same as fish fin. Thus in these simulations we only consider dorsal portions of the full fin and this allows us to clearly establish which portion of the fin is responsible for most of the thrust production.
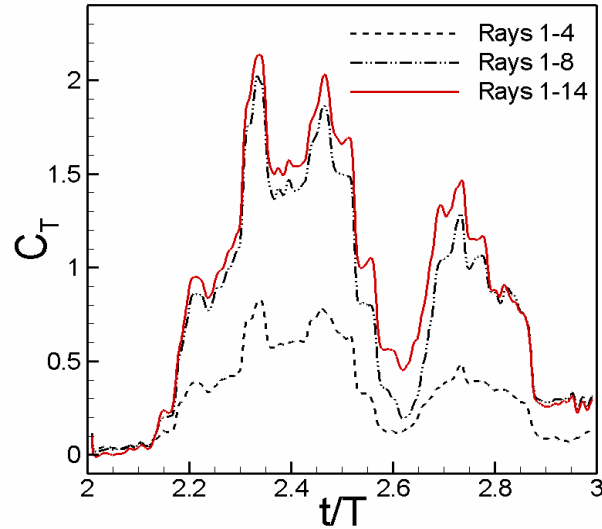

Figure 4. Comparison of time variation of thrust coefficient for three different fin planforms (rays 1-4, rays 1-8, full planform) at $\mathrm{Re}_\infty = 1440$ and $St = 0.54$ while the fin rays are undergoing Mode-1+2+3 gait.

The time variations of the thrust coefficient for three fin planforms are plotted in Figure 4. It is seen that dorsal half of the fin (rays 1-8) captures two main peaks of the thrust closely and achieves almost 90% of the thrust production of full fin planform (rays 1-14). Based on this plot, the effect of ventral side of the fin, represented by ray-9 to -14 in Figure 3, is insignificant to thrust production. The other planform interpolated from rays 1-4 has a similar trend in thrust variation during the entire fin-beat cycle with smaller amplitudes. Interestingly, it has two main peaks (one in the abduction and one in the adduction) and even two local peaks exist in the abduction phase as in full fin planform case. This planform produces almost 40% of the thrust produced by full fin planform while undergoing Mode-1+2+3 gait. These results clearly show how the dorsal leading edge of bluegill's pectoral fin controls the overall performance during propulsion. Also, the key observation here is that the dorsal half of the pectoral fin (rays 1-8) produces almost 90% of the thrust by itself. It could therefore be surmised at this point that the reason for retaining the ventral portion of the fin is to facilitate maneuvering movements.

IV.   Cupping Fin Prototypes

It was shown numerically and experimentally that the sunfish pectoral fin generated positive thrust throughout the fin beat and that peaks of thrust were generated during both the outstroke and the instroke (Figure 2). The complete fin movement that produces these forces is complex, but a simpler gait synthesized from the first three POD modes was predicted to produce 92% of the fin's thrust and to account for 67 % of the fin's total motion. Although the modes interact nonlinearly to produce the thrust, the CFD simulation showed that Mode-1, which is a cupping and sweep motion, was able to produce positive thrust throughout the fin beat without being combined with any other modes. Thus it was decided to investigate the cupping and sweep motion as the primary mechanism for producing positive thrust by developing a robotic fin that replicated closely the motions presented by POD Mode-1. Numerical simulations also suggested that the shape of the sunfish fin should not be underestimated – that it's asymmetric shape was advantageous to moving the fin into a flow, for giving the fin the desired passive flexibility, and for directing thrust along the direction most needed by the fish.

A series of bio-robotic fins were developed to recreate closely the movements and dynamics simulated for the sunfish pectoral fin during POD Mode-1 (Figure 5), and to investigate the effect of fin flexibility on force production. The basic design for these robotic fins used five fin rays of lengths proportional to those of the sunfish pectoral fin that are attached to small diameter hinges mounted into a curved, rigid base. The curvature of the base causes the individual fin rays to move along paths that made the fin cup as the rays were swept forward. The fin rays and the fin webbing were flexible, which allowed for a dynamic interaction between the fin and the water to exist, but the fin ray bases were constrained to rotate within planes defined by the location of the hinge rotation points, the curvature of the base, and the angle the hinges were placed within the base. The location and angular placement of the hinges were defined by analyzing the trajectories of the sunfish fin rays 1, 4, 7, 10, and 14 during Mode-1. Of the sunfish fin's 14 fin rays, these five rays were selected because they appeared visually to define best the shape and curvature of the fin throughout the fin beat. The cross-sections of the fin rays were designed so that the five-ray robotic fins had a flexibility that varied along the length and chord of the fin in a manner similar to that for the biological, sunfish fin.

These fins successfully produced thrust during both the fin's outstroke and instroke, and at the lower flow velocities produced thrust even as the fin transitioned from the outstroke to the instroke (Figure 6). The magnitude of the force was dependent on flapping frequency and flow velocity, but in general, two thrust peaks were produced; a small one as the fin cupped forward and swept into the flow, and a larger peak as the fin uncupped and was swept back. In contrast to the CFD simulations, the fins produced positive thrust throughout the fin beat even when there was zero flow rate. As the velocity of the flow was increased, the magnitude of the thrust decreased, and drag occurred when the fin transitioned from the outstroke to the instroke. The data from test trials conducted with fins of different stiffness at numerous flapping speeds and flow rate suggest that to maximize thrust, fin flexibility must be tuned to flapping frequency and flow rate. Of three prototype fins created, each tended to produce the highest magnitudes of thrust, during both the outstroke and the instroke, at a particular flapping frequency (Figure 7), and visually, the fin's flapping motion appeared to be in resonance when the fin was flapped at that frequency.
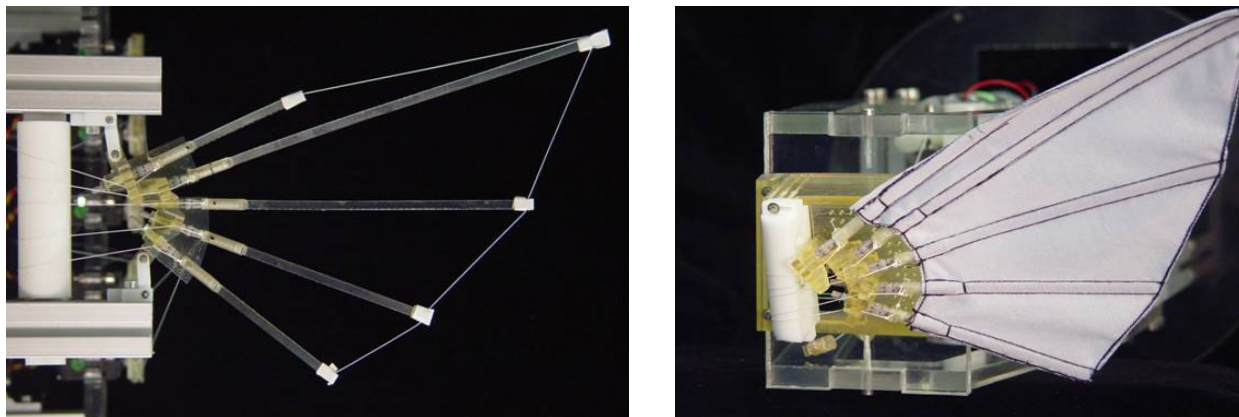

Figure 5. The skeleton and curved base of the five-ray fin are shown at left. The full fin assembly is shown at the right attached to the actuator module. The flexible fin rays are covered in a membrane made from a non-absorbent 0.33 mm polyester-elastane weave.

V.   Conclusion

This work was focused on understanding the controlled and highly complex movements and the associated hydrodynamics of the bluegill sunfish's pectoral fin so that the lessons can be applied to a flexible maneuvering propulsor for AUVs. POD is employed to extract the minimal essential features of the fin motion. The Cartesian grid based immersed boundary solver has been used to investigate underlying physical mechanisms of pectoral fin hydrodynamics. The effect of fin kinematics on the superior hydrodynamic performance of the fish fin has been analyzed using CFD so that the most necessary features can be incorporated into bio-robotic fin design. CFD has also been employed to answer a number of "what if" questions that leads to significant insight into the underlying mechanisms. A series of bio-robotic fins have been designed to replicate Mode-1 movement of sunfish's fin using a close platform to the fish fin. They successfully produced thrust during both the fin's outstroke and instroke. Other POD modes such as Mode-2 and Mode-3 can be superimposed to this design to reproduce higher order approximations (Mode-1+2 and Mode-1+2+3) to the fish fin motion to increase the thrust performance.
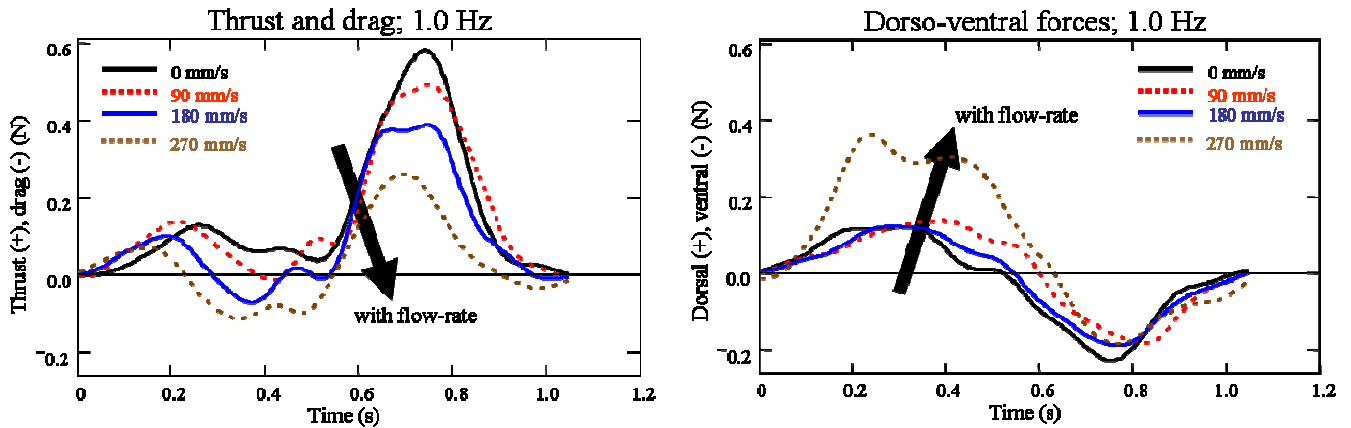
Figure 6. Thrust and drag (left), and Dorso (lift) and ventral (downward) forces produced by the cupping-fin when actuated at a rate of 1 Hz and with flow rates of 0, 90, 180, 270 mm/s. Thrust is reduced, and lift is increased as flow speed rises.
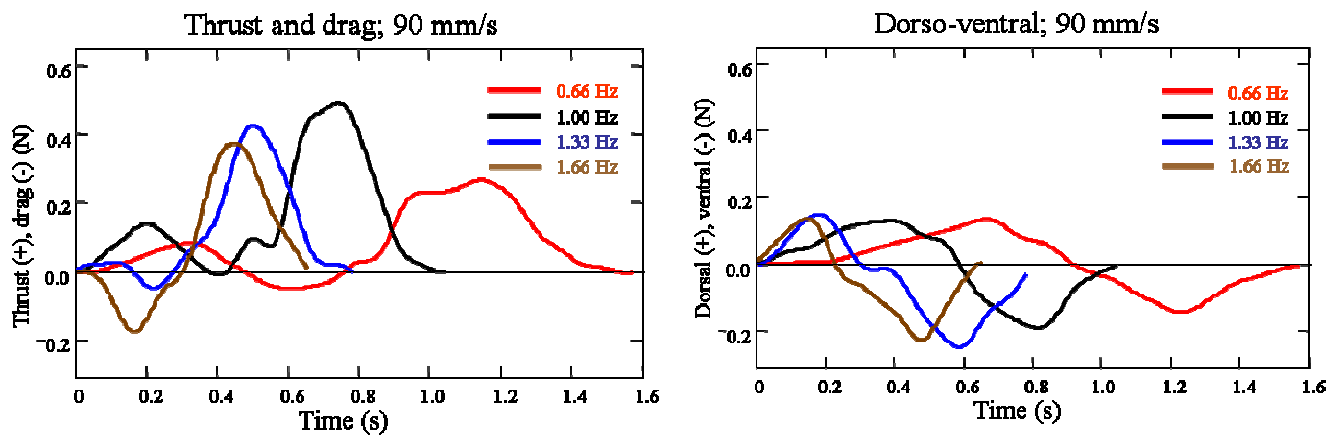

Figure 7. Fin forces and flapping frequency. During both the out-stroke and in-stroke, the maximum magnitude thrust occurred when flapping frequency was tuned appropriately to flow rate and fin flexibility.

Acknowledgment

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