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Understanding the Hydrodynamics of Swimming: From Fish Fins to Flexible Propulsors for Autonomous Underwater Vehicles

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Abstract. The research effort described here is concerned with developing a maneuvering propulsor for an autonomous underwater vehicle (AUV's) based on the mechanical design and performance of sunfish pectoral fin. Bluegill sunfish (*Lepomis macrochirus*) are highly maneuverable bony fishes that have been the subject of a number of experimental analyses of locomotor function [5, 6]. Although swimming generally involves the coordinated movement of many fin surfaces, the sunfish is capable of propulsion and maneuvering using almost exclusively the pectoral fins. They use pectoral fins exclusively for propulsion at speeds of less than 1.1 body length per second (*BL/s*). The curve in Fig. 1 depicts two peaks of body acceleration of bluegill sunfish during steady forward swimming. These abilities are the direct result of their pectoral fins being highly deformable control surfaces that can create vectored thrust. The motivation here is that by understanding these complex, highly controlled movements and by borrowing appropriately from pectoral fin design, a bio-robotic propulsor can be designed to provide vectored thrust and high levels of control to AUVs. This paper will focus on analyses of bluegill sunfish's pectoral fin hydrodynamics which were carried out to guide the design of a flexible propulsor for AUV's.

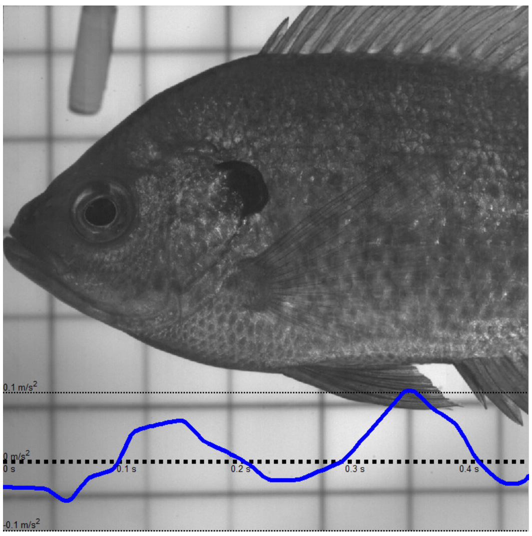


Figure 1. Bluegill sunfish (*Lepomis macrochirus*) where blue curve shows the body acceleration in the flow direction.

Introduction

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 [5]. First, we have undertaken a detailed investigation of 3D kinematic patterns exhibited by fish fins during steady forward swimming. Second the mechanical properties of the fin rays and membrane that comprise the propulsive surface have been measured. 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 carried out 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 flexible engineered fin. Sixth, bio-mimetic, physical, robotic models of the fin have been developed that can reproduce the complex fin motions that fishes use for propulsion and maneuvering.

A first generation, functional, prototype of the bio-robotic fin was produced by the Bioinstrumentation Laboratory at MIT [11]. The architecture of the first generation of the bio-robotic pectoral fin called as "flex fin" was inspired by the anatomy of the bluegill's 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 [1]. 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 [1]. 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 [11]. 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.

Low dimensional Models of Fish Fin Kinematics and Associated Hydrodynamics

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) [5]. 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 [5, 6] as well as numerical simulations of experimentally extracted fin kinematics [9] 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 [7]. 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. [7]. 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 Fig. 2 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 [3]. 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.

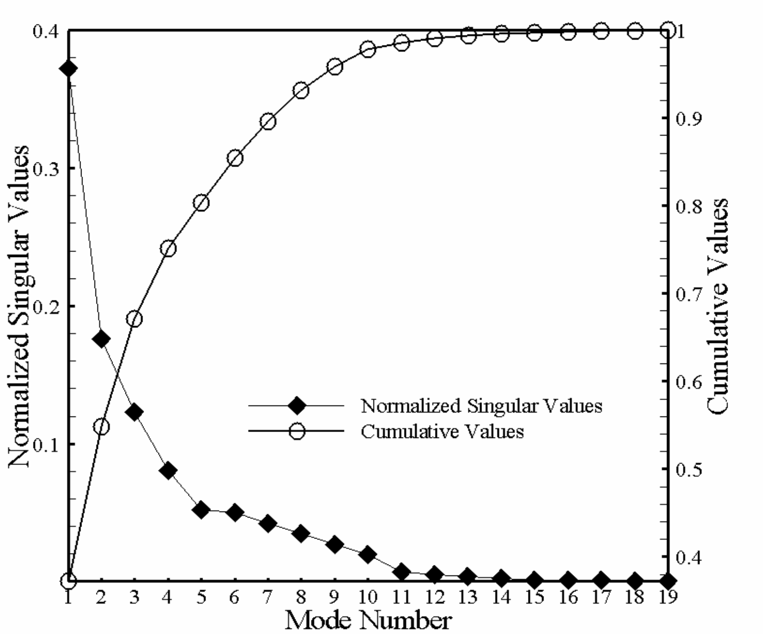


Figure 2. Normalized singular and cumulative values extracted from POD analysis of bluegill sunfish pectoral fin movements during steady forward swimming.

We have developed a finite difference based Navier-Stokes solver with immersed boundary methodology to handle complex 3D biological flow problems [2, 3, 4, 10]. 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.

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) [3]. 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 υ are the fish forward velocity, spanwise size of the fin and the kinematic viscosity respectively) and St (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 ×4.5 L_s ×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 Fig. 3. 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 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 Fig. 2). 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 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.

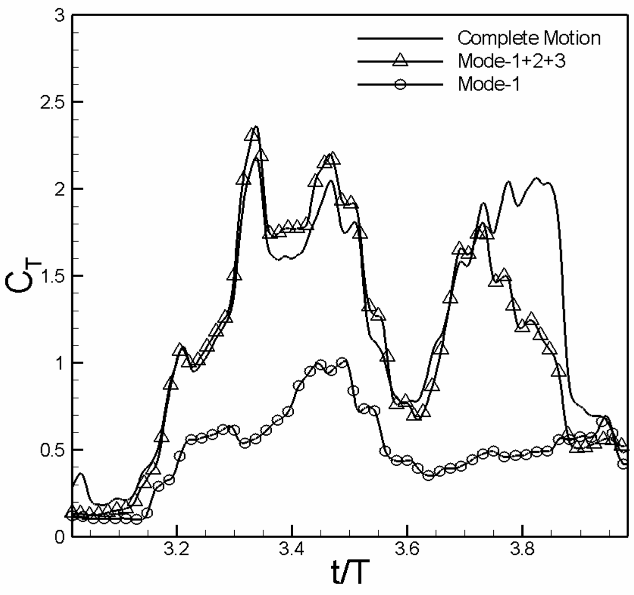


Figure 3. Comparison of time variation of thrust coefficient between complete motion and POD synthesized gaits at $\mathrm{Re}_\infty = 6300$ and $\mathrm{St} = 0.54$.

Scaling Effects on Fin Performance

For a fixed fin gait, two non-dimensional parameters that can potentially affect the performance of the fin are the Reynolds number ($\mathrm{Re}_\infty = U_\infty L_S / \nu$) and Strouhal number ($\mathrm{St} = L_S f / U_\infty$). Examination of the scaling of the performance with these two parameters allows us to gain better insight into the fundamental mechanisms as well as address the practical question of how the performance of fin is expected to change with changes in size, speed and frequency. POD based Mode-1+2+3 gait have been studied to assess the scaling effects.

In basic fluid mechanics, Reynolds number represents the ratio of inertial forces (ρU_∞) to the viscous forces (μ / L), where ρ and μ are the density and the dynamic viscosity of the fluid respectively, U_∞ is the freestream velocity and L is the characteristic length of the flow. In the current application, two values that might change the Reynolds number are the velocity and the size of the fin which are also related to each other as the velocity of the fish is defined in terms of body length per second. This means that when the size of the fin (length scale) is reduced by a factor of two Reynolds number comes down by a factor of four.

In the first set of simulations, Reynolds numbers of 540, 1140, and 6300 have been tested which represent a range spanning an order-of-magnitude. In these simulations, the Strouhal number is kept constant at the nominal value of 0.54. The relatively small variation of the pressure forces on the fin for the three Reynolds numbers (see Fig. 4) indicates that the essential fluid dynamic mechanisms are unchanged with Reynolds numbers and this is quantitatively confirmed by examining the vortex structures for these cases [1]. Table 1 summarizes the time-averaged values of the force components and propulsive efficiency values. Pressure and shear component of the forces are both included in time-averaged performance results. The best hydrodynamic performance is at the bluegill's operating flow regime, $\mathrm{Re}_\infty = 6300$. Lower Reynolds number cases not only produce slightly less pressure thrust but also generate more shear drag which together reduce total thrust production. Besides generating the highest thrust value, $\mathrm{Re}_\infty = 6300$ case also creates less lift force than lower Reynolds number cases. As a result, it is the most efficient fin gait between the three tested so far (see last column of Table 1).

Table 1. Reynolds number effect on fin performance for POD Mode-1+2+3 gait at $St = 0.54$.

Re_∞	St	$\overline{C_T}$	$\overline{C_L}$	$\overline{C_Z}$	η
540	0.54	0.66	0.35	-0.26	0.45
1440	0.54	0.84	0.32	-0.26	0.48
6300	0.54	1.09	0.29	-0.26	0.53

In the next set of simulations, the effect of Strouhal number on the fin performance was examined. The Reynolds number for this study is fixed at 1440. Three different cases, $St = 0.41, 0.54, 0.7$, were studied and within this context; change in Strouhal number may be interpreted as change in the ratio of the speed of the fin-tip to speed of forward travel. The Strouhal number estimated for the bluegill's pectoral fin in steady forward motion is 0.54. A lower and a higher frequency case which represent a lower relative tip-speed and a higher relative tip speed respectively have been tested.

Table 2. Strouhal number effect on fin performance for POD Mode-1+2+3 gait.

St	Re_∞	$\overline{C_T}$	$\overline{C_L}$	$\overline{C_Z}$	η
0.41	1440	0.69	0.3	-0.23	0.37
0.54	1440	0.84	0.32	-0.26	0.48
0.7	1440	1.02	0.34	-0.27	0.29

Time-averaged values of three components of force coefficients and efficiency values are given in Table 2 for three St cases studied so far. First thing to notice is that hydrodynamic performance of the fin is quite sensitive to the St. As it is also seen in Fig. 5 thrust production increases linearly with the flapping frequency. The maximum thrust is produced by the highest St number case

($St = 0.7$), which is about 21% more than the fish operating point ($St = 0.54$). On the other hand, the propulsive efficiency has a peak value at $St = 0.54$ and drops dramatically with an increase in the frequency. It clearly indicates that fish selected the optimum frequency required for the steady forward swimming and detailed investigation of fish pectoral fin motion is the right approach to design flexible maneuvering propulsor for AUV's. Fig. 6 shows vortex structures for this set of simulations at the end of fin-beat cycle. Main features of the vortex structures look similar for the three cases; however one can still notice that tip vortex gets stronger with an increase in St number.

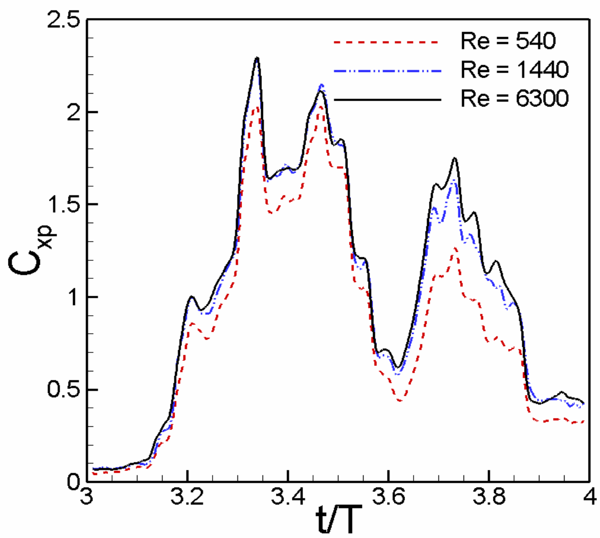


Figure 4. Time variation of thrust coeeficient due to pressure at three different Reynolds numbers for POD Mode-1+2+3 gait at $St = 0.54$.

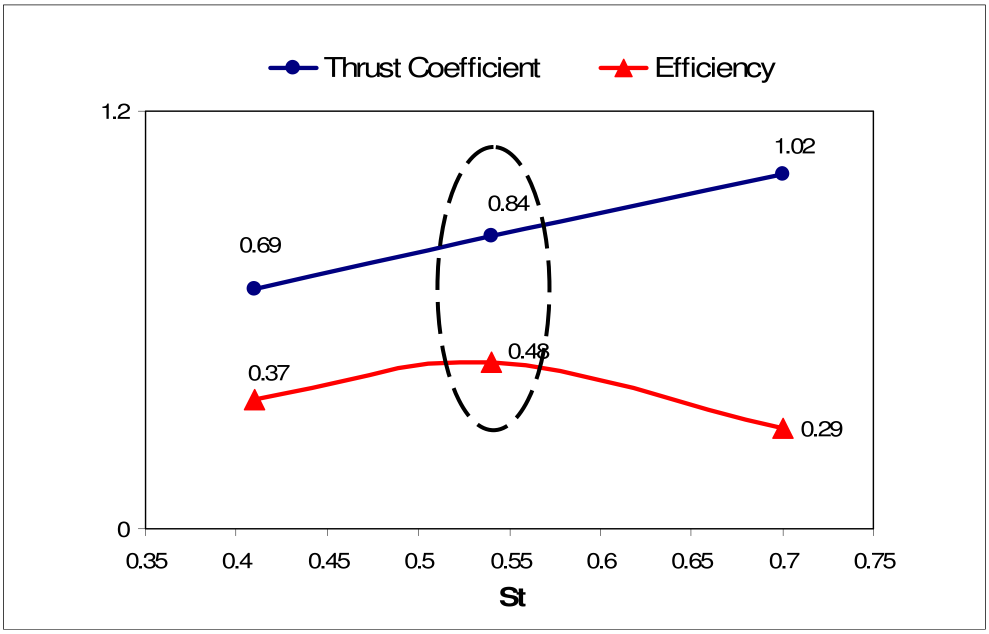
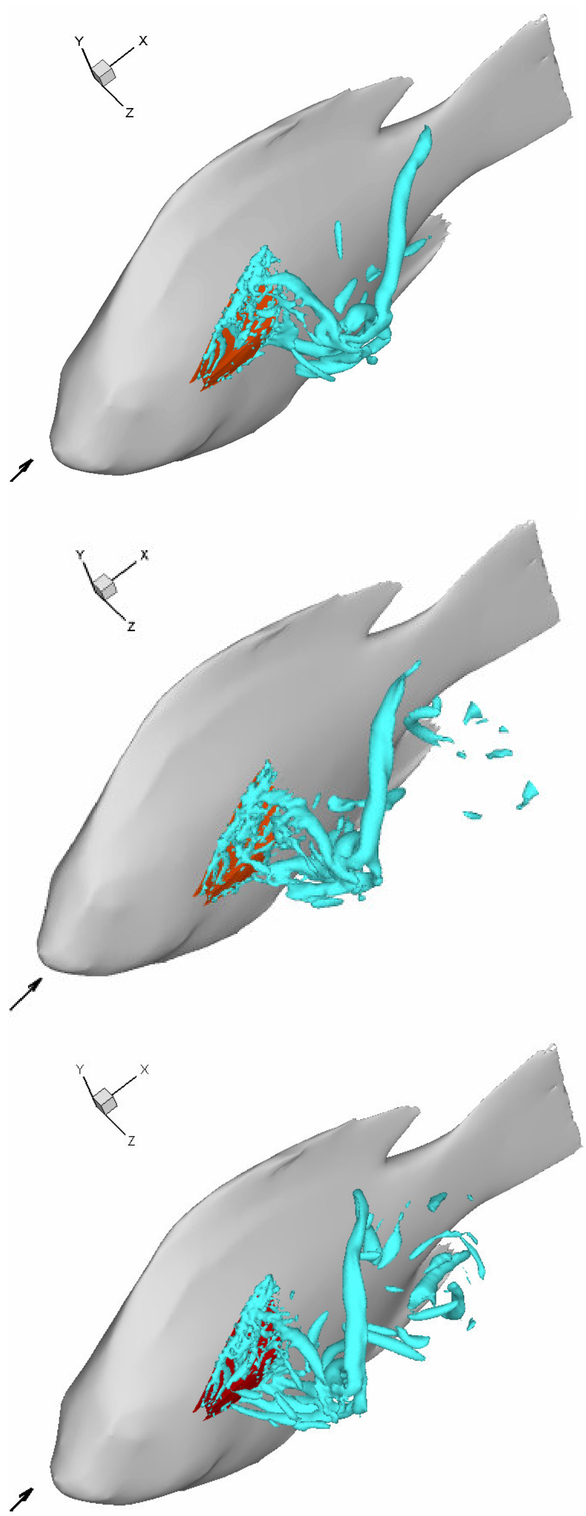


Figure 5. Hydrodynamic performances of three St cases where the best performance case is at the fish operating frequency corresponding to $St = 0.54$.



(a) t/T= 1.0, $St = 0.41$

(b) t/T= 1.0, $St = 0.54$

(c) t/T= 1.0, $St = 0.7$

Figure 6. St effect on wake structures for POD Mode-1+2+3 gait at $\mathrm{Re}_{\infty} = 1440$.

Cupping Fin Prototypes

It was shown numerically and experimentally that the sunfish pectoral fin generated positive thrust throughout the fin beat and two peaks of thrust were generated during both the outstroke and the instroke (Fig. 1 and Fig. 3). 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. Also this gait is the most efficient gait with 73% efficiency value between all the gaits studied with CFD so far. 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 (Fig. 7), 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 (Fig. 8). 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. 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 (Fig. 9), and visually, the fin's flapping motion appeared to be in resonance when the fin was flapped at that frequency.

Summary

By studying the steady swimming of sunfish and appropriately barrowing the crucial features of its mechanical design and motion, we have developed a bio-robotic fin propulsor with characteristics that are advantageous for propelling and maneuvering AUVs. POD analyses worked effectively to extract the minimal essential features of the fin motion. The effect of fin kinematics on the superior hydrodynamic performance of the fish fin has been analyzed using Cartesian grid based CFD technology. 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 planform to the fish fin. They successfully produced thrust during both the fin's outstroke and instroke. We are currently conducting efficiency studies of these robotic fins to improve thrust production and control of propulsion and maneuvering forces further. CFD is also being used to study bio-robotic fin hydrodynamics during locomotion in detail and the results will be presented soon.

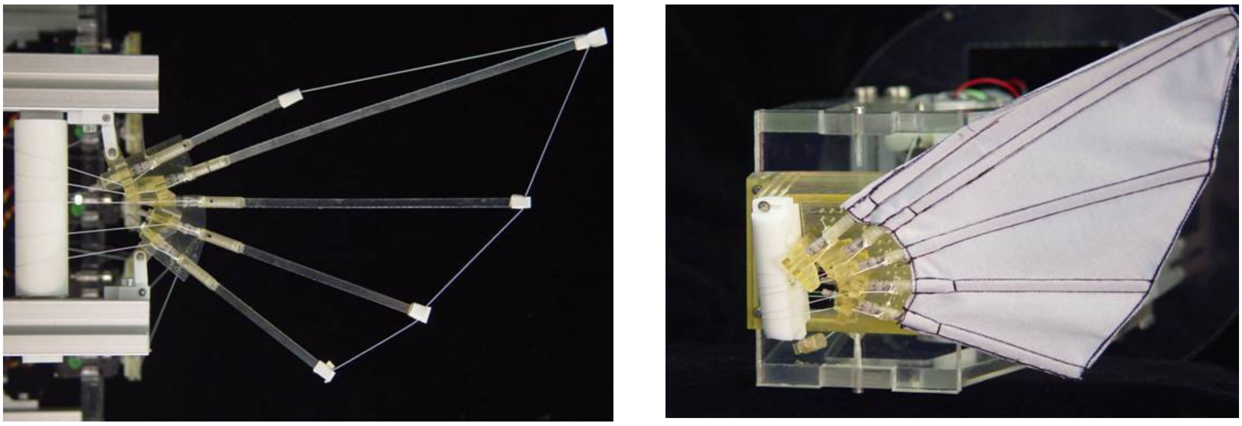


Figure 7. The skeleton and curved base of the five-ray fin are shown at left. The full fin assembly is shown at the right attached to the actuator module. The flexible fin rays are covered in a membrane made from a non-absorbent 0.33 mm polyester-elastane weave.

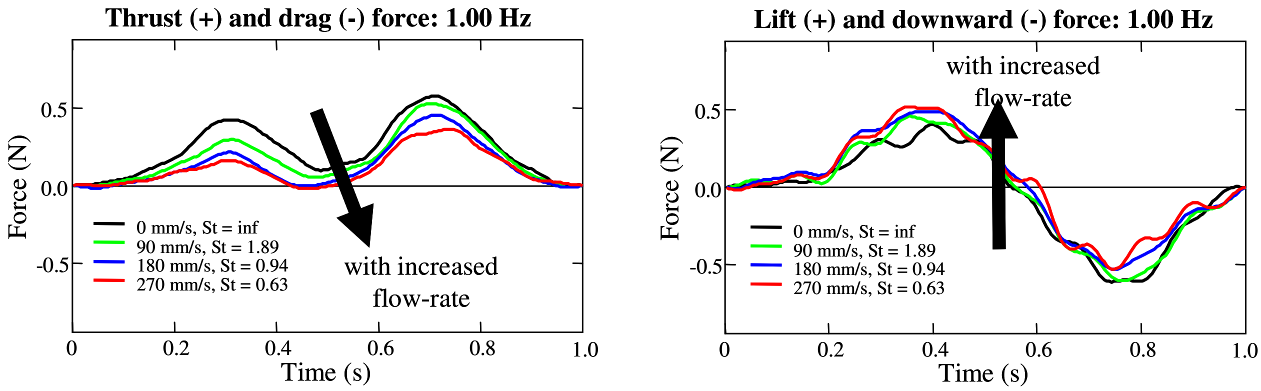


Figure 8. Fin forces at different flow rates. Thrust and drag (left), and dorsal (lift) and ventral (right) forces produced by a cupping-fin when actuated at a rate of 1.00 Hz. Thrust is reduced, and lift is increased as flow speed rises.

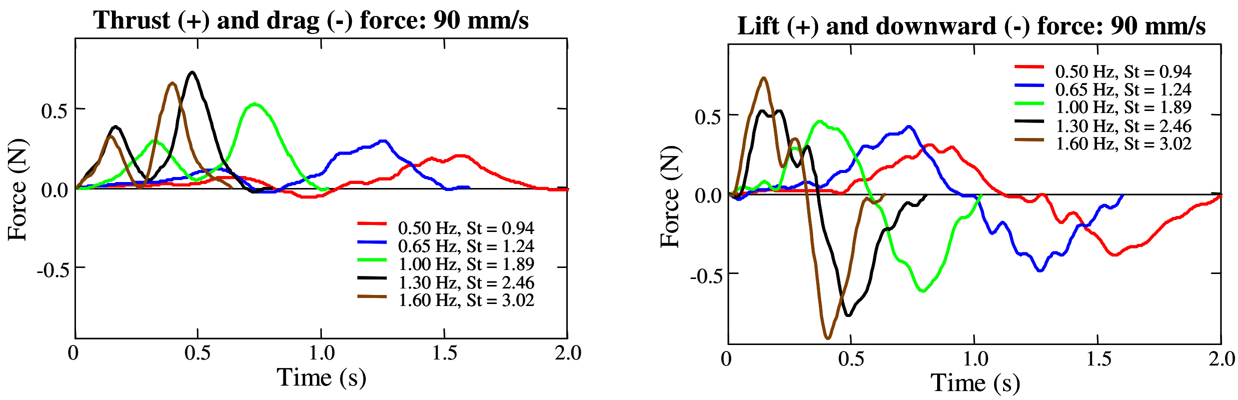


Figure 9. Fin forces at different flapping frequencies. During both the outstroke and instroke, the maximum magnitude of thrust occurred when flapping frequency was tuned appropriately to flow rate and fin flexibility.

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