Abstract—We present experimental results of thrust produced by a robotic propulsor, the design of which is inspired by the ribbon fin of the South American black ghost knifefish (*Apteronotus albifrons*). This remarkably nimble fish moves by oscillating its ribbon fin rays out of phase and thereby passing a traveling wave along the fin’s length. Combinations of thrust from the ribbon fin and body rolls produced by the two pectoral fins enable the black ghost to swim in nearly any direction without bending its body. The fish’s agile locomotor system is tightly integrated with its omnidirectional, active sensing system. The robotic ribbon fin has eight individually actuated metal rays which are linked by a thin latex sheet. The experimental results demonstrate the effect of varying the propulsive wave’s frequency, amplitude and length on the robotic fin’s thrust production. We found that thrust production peaks at particular combinations of the three variables and that the fin could produce steady forward thrust, despite the relatively small number of rays. The robotic ribbon fin has potential application as a propulsor for future underwater vehicles, in addition to being a valuable scientific instrument in understanding the swimming mechanics of the black ghost and similar fish.

Index Terms—biomimetics, underactuated, black ghost knifefish

I. INTRODUCTION

A. Prior Work

This effort builds upon the prior work of MacIver, Fontaine and Burdick [1] who built a similar ribbon fin for self-propelled swimming. The authors introduced a smaller design in [2] and in this paper present experimental measurements of thrust produced by an improved mechanism. We compare those results to the thrust predicted by a simplified hydrodynamic model which was adapted from the work of Sfakiotakis and Tsakiris [3], McIsaac and Ostrowsky [4, 5] and Ekeberg [6].

B. Black Ghost Knifefish

The black ghost knifefish (*Apteronotus albifrons*) is a remarkably nimble fish which inhabits sandy-bottomed rivers and creeks from Venezuela to Paraguay. An adult black ghost is typically 13–50 cm long and has a single, ribbon-like fin which runs along most of its underbelly (see Fig. 1). The fin is supported and actuated by about 100 bony rays, arranged in a series like the teeth of a comb. An adult which is ~13 cm long has a ribbon fin ~10 cm long, with rays spaced ~1 mm apart.

The rays in the middle section of the fin are ~1 cm long and become progressively shorter as the fin tapers at its anterior and posterior margins. The fish also has two pectoral fins, located on either side of the body towards the front, which it uses for steering and stability [1, 7].

The black ghost generates a weak electric field, ~1 mV/cm in the region near its body, to sense the environment, communicate with conspecifics and locate prey such as tiny insect larvae and crustaceans. The black ghost’s ability to accelerate in multiple directions enables effective coverage of all points within its omnidirectional sensing volume [1, 8, 9].

The fish propels itself by oscillating the ribbon fin rays slightly out of phase, thereby producing a traveling wave along the fin, while keeping its thin, flat body mostly rigid [8, 10]. The propulsive wave travels in the direction opposite to that of the body’s motion. By passing the traveling wave from tail to head, the fish is able to swim backward with the same ease with which it swims forward [11]. The black ghost can also move laterally towards objects detected alongside its body by pairing a translation with a roll about its head-to-tail axis and actuating the ribbon fin so as to move upwards in the body frame (heave motion) [1, 8]. This is an unusual behavior for fish, whose deep body plans are interpreted as providing stability to counter roll [12], but it is an effective mechanical solution for movement in unactuated directions.

Fig. 1: South American black ghost knifefish (*Apteronotus albifrons*) with ribbon fin on its underbelly. One of the two pectoral fins is visible to the right of the head. Photo from [13].
C. Propulsive Wave

We can model the propulsive wave as a basic sinusoid, formed by all the fin rays oscillating at the same frequency but out of phase. The orientation of the \( n \)-th ray at time \( t \) is:

\[
\theta(n, t) = \Theta \sin[2\pi ft - \varphi(n)]
\]  

(1)

where \( \theta \) is the angular deflection from the vertical, \( \Theta \) is the maximum angular deflection and \( f \) is the frequency in hertz; \( \varphi \) is the phase delay as a function of ray number and is:

\[
\varphi(n) = 2\pi \frac{n - 1}{N - 1} \frac{L}{\lambda}
\]  

(2)

where \( N \) is the total number of rays, \( \lambda \) is the wavelength and \( L \) is the fin length. From the above equations, we can see that as the wavelength increases, the phase difference between rays drops. Therefore, more rays are available to ‘sample’ each wave cycle apparent in the fin, and the fin takes on a smoother, more sinusoidal and less saw tooth shape.

II. ROBOTIC RIBBON FIN

The robotic ribbon fin has eight rays connected by a 0.025 mm thick sheet of latex. Each ray is a brass rod, 76.2 mm in length and 1.6 mm in diameter. The distance from the tip of the first ray to the tip of the eighth, when the fin is in its quiescent state, is 231 mm.

The rays are individually actuated by radio-controlled (RC) servo motors (JR/Horizon, Champaign, IL, USA; model DS168). They have a range of 40° in either direction from the rotor center and a rotational velocity equivalent to 71 rpm (at 4.8 volts). A pair of miter gears transmits torque from each motor to the corresponding ray. The motors are controlled by pulse width modulated signals generated by a microcontroller (Yost Engineering, Inc., Portsmouth, OH, USA; ServoCenter), which is connected by RS232 serial interface to a Windows® PC. Custom MATLAB code issues rotor position commands to the microcontroller. The fin was designed with commercial, three-dimensional modeling software (SolidWorks Corp., Concord, MA, USA; SolidWorks) and all structural parts are aluminum 6061 alloy sheet metal, cut on a high-speed CNC milling machine.

III. EXPERIMENTS

A. Objective

Our objective was to measure the effect on thrust production of varying the propulsive wave’s frequency, amplitude and wavelength.

B. Test Bed

The robotic ribbon fin was suspended so that the top of the latex sheet hung below the water line in a large agricultural trough (Rubbermaid Commercial Products, Winchester, VA, USA; model 4245). Above the water line, the fin was mounted on a precision ball-bearing, linear slide assembly (Parker Automation, Irwin, PA, USA; model 4201) which was connected to one side of a 9 N-capacity, tension and compression load cell (Futek Advanced Sensor Technology, Irvine, CA, USA; model L2357); the opposite side of the load cell was fixed to mechanical ‘ground,’ as shown in Fig. 2. The load cell’s analog voltage output was passed first to a signal amplifier and then sampled at 2 kHz by a 16-bit National Instruments data acquisition system. The resolution of the measurements was approximately 0.1 mN.

C. Variables

The variables in this experiment were the three characteristics of the sinusoidal propulsive wave, namely frequency, amplitude and wavelength. Instead of the absolute wavelength, however, we used the non-dimensional ratio of wavelength to fin length, i.e. the specific wavelength [10], and rather than amplitude, we used the maximum angular deflection of the constitutive rays to either side of the vertical. The wave amplitude, \( A \), maximum ray deflection, \( \Theta \), and ray length, \( r \), are related by:

\[
\sin(\Theta) = A/r
\]  

(3)

We define a three-dimensional “wave space” and assign each of the three characteristics to an axis. A sinusoidal propulsive wave can then be fully described by the coordinates of a point in this space:

\[
p = [f \quad \Theta \quad w]
\]  

(4)
where $p$ is a vector from the origin to a point in wave space, $f$ is the frequency of the wave in hertz, and $w$ is the non-dimensional specific wavelength:

$$w = \frac{\lambda}{L} \quad (5)$$

We delineate the region $D$ of feasible points in wave space as:

$$D = \left\{ (f, \Theta, w) : 0 < f \leq 3, 0 < \Theta \leq 35, 0 < \frac{1}{w} \leq \frac{N-1}{2} \right\} \quad (6)$$

The frequency limit arises from the maximum speed of the actuator motors. The specific wavelength limit reflects the largest number of complete cycles which can be formed by eight rays and this occurs when each ray is one half-cycle out of phase with any adjacent rays. The maximum number of cycles visible in the fin is then 3.5, the reciprocal of which is the minimum specific wavelength. The amplitude limit comes from the observed behavior of the knifefish [1, 10].

For the experimental trials, we chose equally-spaced points in the feasible region of wave space. They are:

$$p_{ijk} = \left[ f_i, \Theta_j, w_k \right]$$

$$f_i = 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 \ (\text{Hz})$$

$$\Theta_j = 10, 15, 20, 25, 30, 35 \ (\text{degrees})$$

$$w_k = 0.7, 1.4, 2.1, 2.8, 3.5, 4.2 \quad (7)$$

We then measured the thrust produced by the ribbon fin, conducting two to three trials for each of the 216 values of $p_{ijk}$, for a total of 562 trials.

D. Trial Protocol

Each trial was divided into four phases. The first phase lasted one second, during which the data acquisition system was active, but all actuators were off. The purpose of this phase was to capture any sensor bias and to establish a baseline for subsequent force measurements. A non-zero force reading in this phase might occur if the slide assembly was not on a truly level surface, or if friction in the slide inhibited the load cell from returning completely to the quiescent position at the conclusion of the previous trial.

The second phase of each trial also lasted one second and began with the activation of the motors. The purpose of this phase was to allow any transient forces to diminish before collecting steady thrust data.

The third phase lasted five seconds and was intended to measure the steady-state thrust production. The average of the readings from this phase, less the average of the readings from the first phase, was taken as the mean thrust production for the trial as a whole.

Finally, in the fourth phase, the actuators were turned off, data capture was halted and the water was allowed to settle for 35 seconds before the start of the next trial.

E. Results

Mean values for all trials of similar frequency, maximum ray deflection and specific wavelength are plotted in Fig. 3, Fig. 4 and Fig. 5; each graph provides a different perspective on the set of results. A selected subset of the results appears in tabular form in Table I. For comparison, the plots also display thrust production as predicted by a simplified hydrodynamic model, detailed in [2] and based on the prior work of Ekeberg [6], Sfakiotakis and Tsakiris [3] and Mclsaac and Ostrowski [4] in analyzing the forces on swimming, eel-like robots. Ekeberg based his model on Taylor’s groundbreaking Analysis of the Swimming of Long and Narrow Animals [14].

We can see that thrust production peaks at particular values of the propulsive wave variables. These peaks are most evident in the upper right quadrant of each figure, and where there is a peak, it occurs at approximately the same value of the independent variable.

The hydrodynamic model does well at predicting the wavelength which coincides with peak thrust production, especially at higher frequencies and maximum ray deflections. We see in Fig. 5, especially in those sub-plots toward the upper right corner, that both the experimental and model curves peak at the same specific wavelength, usually 1.4. The model fares less well, however, in matching the trends of experimental thrust production that accompany varying frequency and maximum ray deflection. Fig. 3 and Fig. 4 show that the model predicts a continuous upward trend in thrust production, while the experimental results indicate a clear leveling-off in thrust at higher maximum ray deflections and frequencies.

<table>
<thead>
<tr>
<th>$f$ (Hz)</th>
<th>$\Theta$ (deg)</th>
<th>$w$</th>
<th>Model-Predicted Thrust (mN)</th>
<th>Measured Thrust (mN)</th>
</tr>
</thead>
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<tr>
<td>0.5</td>
<td>10</td>
<td>0.7</td>
<td>1</td>
<td>5</td>
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<tr>
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<td>35</td>
<td>4.2</td>
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</tr>
</tbody>
</table>

IV. CONCLUSION

The experimental results show the effect on thrust production of varying the frequency, amplitude and wavelength of the propulsive wave in the ribbon fin, and we see that thrust peaks at particular values of all three wave characteristics. As the wavelength decreases and the phase difference between any two successive rays increases, the sinusoidal wave takes on a sharper, more saw tooth shape. Model-based simulation shows that sections of the fin generate significant reverse thrust during such short wavelength undulation. However, as the wavelength increases, both the phase difference between successive rays and the
number of cycles in the fin tend toward zero. The rays oscillate more in unison and the motion of the fin becomes increasingly side-to-side flapping and less front-to-back undulation, with a resulting drop in thrust. We expect, then, to find a point where the thrust peaks with a varying wavelength. Indeed, both the experimental and model data indicate such a peak, and at approximately the same specific wavelength, as shown in Fig. 5.

The leveling-off of thrust production that accompanies an increased maximum ray deflection could be attributed to a greater load on the rays. As they oscillate to higher angles, especially at shorter wavelengths when the rays are more out of phase, the latex sheet is increasingly stretched and may tend to bend the rays, or even restrict them from reaching the full, prescribed angle of deflection.

The simplified hydrodynamic model [2] usually underestimated the measured thrust and did not foretell the peaking of thrust production. The model treats the fin as if it were a mesh of infinitely thin, smooth, flat plates, with each plate moving in a stationary fluid and contributing independently to the thrust. Much of the apparent discrepancy between the model-predicted thrust and that which was measured is likely due to the fact that the model does not account for the interaction between plates and the effect a plate’s motion has on the fluid surrounding neighboring plates. We are currently formulating an improved model based on the experimental results.

ON-LINE RESOURCES

Photographs and video of the robotic ribbon fin and a copy of this paper are available at the following web link: http://www.neuromech.northwestern.edu/publications

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REFERENCES


Fig. 3: Thrust production vs. frequency of the propulsive wave. The red lines and circular markers indicate experimentally measured thrust production. The gray lines and square markers indicate model-predicted thrust production [2] using a drag coefficient of 1.28 (lower gray lines) and 2.00 (upper gray lines).

Fig. 4: Thrust production vs. maximum ray deflection. The red lines and circular markers indicate experimentally measured thrust production. The gray lines and square markers indicate model-predicted thrust production [2] using a drag coefficient of 1.28 (lower gray lines) and 2.00 (upper gray lines).
Fig. 5: Thrust production vs. specific wavelength of the propulsive wave. The red lines and circular markers indicate experimentally measured thrust production. The gray lines and square markers indicate model-predicted thrust production [2] using a drag coefficient of 1.28 (lower gray lines) and 2.00 (upper gray lines).