Energy efficiency study of an ostraciiform fish robot

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The ostraciiform swimming mode utilizes the caudal fin flapping to achieve piscine propulsion with turning maneuverability. Mechanism can be mimicked and implemented in underwater vehicles and it is necessary to know the energy efficiency of this swimming mode for durability consideration. Present study consists the energy efficiency of a servomotor actuated ostraciiform fish robot through power measurements. The power consumption of actuator (servomotor) was measured directly through an electronic circuit. Power dissipation in hydrodynamic drag during swimming was obtained indirectly from the swimming velocity. Different flapping frequency and amplitude settings were applied to explore the relationship between the flapping condition and efficiency.

[Keywords: Ostraciiform, fish robot, power measurement, energy efficiency]

Introduction

Biomimetic fish robots are regarded as the next generation of underwater vehicles\textsuperscript{1} for marine tasks such as military surveillance, biological researches, and seabed exploration\textsuperscript{2} etc. Fish robot researches incorporate the piscine propulsion into contemporary underwater vehicles and develop effective swimming machines for aquatic applications. Different swimming strategies or locomotions\textsuperscript{3-7} have been developed in natural species for biomimicking. Using Breder’s classification\textsuperscript{4}, swimming locomotions can be classified as body and/or caudal fin (BCF) locomotion, which is favored for accelerating and cruising, and median and/or paired fin (MPF) locomotion, which shows superiority in maneuvering. Present study is based on these swimming strategies to design and develop different fish robots, such as Peking University’s carangiform robot fish\textsuperscript{8}, MIT’s Robotuna\textsuperscript{9}, NMRI PF-300 fish robot\textsuperscript{10} and ITB’s labriform fish robot\textsuperscript{11}.

The ostraciiform swimming mode possesses the highest maneuvering ability out of BCF type, and is a suitable strategy for tasks, which require cruising and maneuvering abilities. The swimming mode exhibits a simple swimming strategy for motion generation in aquatic environment. Hydrodynamic thrust is generated through the oscillation/flapping of caudal fin, which can also serves as a rudder for turning motion. This provides a simple mechanical and control implementation for biomimetic fish robots as well as underwater vehicle designs. Different actuators\textsuperscript{12-14} have been applied in the fish robot designs for swimming locomotion and the choices of actuator can affect the swimming strategy (e.g. frequency and amplitude of actuation) with the energy consideration.

In the swimming of a fish robot, power is dissipated into the hydrodynamic drag, mechanical friction, and actuator operation. The total power dissipation can be measured by monitoring the usage of power source. Useful power for motion is dissipated in hydrodynamic drag, and such dissipation can be measured indirectly from the swimming velocity with the knowledge of drag coefficient and added mass. A common measure of the energy efficiency is the Froude propulsive efficiency\textsuperscript{15}, which is ratio of average hydrodynamic dissipation to the average total power usage.

The present study comprises the energy efficiency of an ostraciiform fish robot, actuated by a servomotor, for different caudal fin flapping conditions. Drag coefficient and added mass were determined through an experimental setup. Hydrodynamic power dissipation for swimming was measured indirectly from the swimming velocity. Power consumption for servo operation and
Mechanical friction was obtained through the current measurement of the servomotor.

**Fish Robot Design**

The fish robot used in the experiments is shown in Fig. 1. The swimming mode is ostraciiform and the thrust is generated by the caudal fin oscillation. Both the body and rear sections (made by rigid acrylic frame) have constant thickness from the side view and are symmetric from the front and top views. The dorsal fin provides buoyancy to maintain the top surface of the robot body about 3 cm below the water surface and to restrict the swimming motion to be 2D. Pectoral fins were attached to increase damping in the rolling and vertical motions.

The length of the fish robot is 26.4 cm (excluding caudal fin), the width is 7.4 cm (excluding pectoral fins), and the height is 8.8 cm (excluding dorsal fin). Including dorsal fin, the frontal cross sectional area $A$ in water about 69.6 cm$^2$ and the mass $m_f$ is 1196 g. The tail part of the fish robot contains an electro-mechanical system with a waterproofed servo (operated at 5 V) for caudal fin oscillation. The axle has two clips attached for caudal fin mounting. All electronic and mechanical components were arranged for body balance and buoyancy adjustment. Caudal fin is replaceable and three 1 mm thick acrylic rectangular caudal fins, namely 2025Rect, 2925Rect and 3825Rect, were applied in the experiments. The dimension of all fins is summarized in Table 1.

**Experiments**

The thrust power for swimming motion was measured indirectly from the hydrodynamic drag dissipation, which required the knowledge of drag coefficient and terminal velocity. An experimental setup was designed to measure the drag coefficient and added mass simultaneously. The terminal velocity, which was not possible to achieve due to the limited pool size, was measured indirectly from the average velocity measurement. Besides the power dissipation in swimming drag, the power consumption in actuator mechanism (e.g., friction, electronics, etc) was measured through an electronic circuit. All experiments were carried out in a circular inflatable pool with the diameter of 154 cm and depth of 25 cm.

**Drag Coefficient and Added Mass Determination**

The drag coefficient $C_d$ and added mass $m_a$ were determined by pulling the fish robot using pulling weights (mass = $m_a$) as shown in Fig. 2. A string (with negligible mass) was connected between the robot and pulling weight through some fixed pulleys. The robot and hence, the weight were held static initially. When the weight fell, the robot was pulled straightly and horizontally toward the bottom pulley. An optical encoder circuit recorded the motion of a pulley, and hence the robot displacement, with time.

Assuming that the air drag on the pulling weight is negligible and the pulley friction $f_c$ is constant, the equation of motion and the solutions (with the initial conditions $x(0) = v(0) = 0$) can be written as

$$M\ddot{x} + 0.5 \rho_s C_d A \dot{x}^2 = m_a g - f_c,$$

$$x(t) = a_t^{-1} \ln \left[ \cosh \left( \sqrt{a_t} \alpha t \right) \right],$$

$\rho_s$ is the density of water, $M$ is the mass of the body of the fish robot, $A$ is the frontal cross sectional area, $C_d$ is the drag coefficient, $f_c$ is the pulley friction, and $\alpha = \sqrt{\frac{0.5 \rho_s C_d A}{M}}$ is a parameter which is constant. The added mass is calculated by

$$m_a = \frac{\rho_s A}{2 \sqrt{\frac{0.5 \rho_s C_d A}{M}}} \int_0^\infty \cosh \left( \sqrt{\frac{0.5 \rho_s C_d A}{M}} t \right) dt.$$

The dimension and aspect ratio (AR) of caudal fins are summarized in Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Height H (cm)</th>
<th>Length L (cm)</th>
<th>Area (mm$^2$)</th>
<th>Aspect Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>2025Rect</td>
<td>6.36</td>
<td>3.18</td>
<td>2025</td>
<td>2</td>
</tr>
<tr>
<td>2925Rect</td>
<td>7.65</td>
<td>3.82</td>
<td>2925</td>
<td>2</td>
</tr>
<tr>
<td>3825Rect</td>
<td>8.75</td>
<td>4.37</td>
<td>3825</td>
<td>2</td>
</tr>
</tbody>
</table>
\[ v(t) = \dot{x}(t) = \frac{a_2}{a_1} \tanh\left(\frac{a_1 a_2 t}{2}\right), \quad \cdots (3) \]

\[ M = m_f + m_a + m_a + m_p, \quad \cdots (4) \]

\[ a_1 = \rho_w C_d A / (2 M), \quad \cdots (5) \]

\[ a_2 = (m_a g - f_p) / M, \quad \cdots (6) \]

where \( \rho_w (=0.997 \text{ g/cm}^3) \) is the water density, and \( m_p (=20 \text{ g}) \) is inertial contribution from the pulley system. Different pulling weights (10 g to 40 g in a step of 5 g) were applied in the experiment. The added mass and drag coefficient were determined by fitting the experimental data with the solution in Eq. 2.

**Velocity Measurement and Hydrodynamic Power Dissipation**

The experimental setup for the velocity measurement is shown in Fig. 3. The fish robot swam forward for \( x_f = x(t_f) = 115 \pm 4 \text{ cm} \), from rest \( (x(0) = v(0) = 0) \). The traveling time \( t_f \) was determined from the video recording of the swimming motion (with the error of \( \pm 0.1 \text{ s} \)), and the average velocity \( v_a \) was determined through

\[ v_a = \frac{x_f}{t_f}, \quad \cdots (7) \]

The equation of motion and the solution \((x(t)\) and \(v(t))\) for the swimming motion are

\[ (m_f + m_a) \ddot{x} + 0.5 \rho_w C_d A \dot{x}^2 = F_p, \quad \cdots (8) \]

\[ x(t) = b_1^{-1} \ln\left[ \cosh\left(\sqrt{b_2} t\right)\right], \quad \cdots (9) \]

\[ v(t) = \dot{x}(t) = \frac{1}{b_1} \tanh\left(\sqrt{b_2} t\right) = v_a \tanh\left(\sqrt{b_2} t\right), \quad \cdots (10) \]

\[ b_1 = 0.5 \rho_w C_d A / (m_f + m_a), \quad \cdots (11) \]

\[ b_2 = F_p / (m_f + m_a), \quad \cdots (12) \]

where \( F_p \) is the average propulsive force and \( v_\infty = (b_2/b_1)^{1/2} \) is the terminal velocity. It can be shown from Eq. 7 and Eq. 9 that the terminal velocity \( v_\infty \) is proportional to the average velocity \( v_a \) as

\[ v_a = \frac{b_1 x_f}{\cosh^{-1}\left[ \exp(b_1 x_f) \right]} v_\infty, \quad \cdots (13) \]

The average velocity of the fish robot was measured for different frequency (from 1.5 Hz to 4.0 Hz in a step of 0.5 Hz) with a fixed flapping amplitude of 16 degree \((\theta_{max} = 16^\circ)\).

When the fish robot is swimming at its terminal velocity, kinetic energy is dissipated to the hydrodynamic drag. Therefore, with the average velocity (and hence the terminal velocity), the hydrodynamic power dissipation \( P_d \) can be computed by

\[ P_d = 0.5 \rho_w C_d A v_\infty^3. \quad \cdots (14) \]

**Servo Power Consumption Measurement**

Beside the hydrodynamic dissipation, energy was also lost mechanically (joint, gear friction and drag on caudal fin, etc) and electrically (circuit inside the servo) during swimming. By measuring the current of the servo during caudal fin oscillation, the power consumption can be determined. The schematic diagram for the servo power consumption measurement is shown in Fig. 4. The fish robot, with oscillating caudal fin, was held fixed underwater during the power consumption measurements.

A shunt resistor \((0.5 \Omega)\) was connected in series to the servo to determine the servo current during caudal fin oscillation in water. The shunt voltage \( V_s \) was amplified in an op-amp circuit with the amplification factor of 5. The amplified signal, which contained many tiny square pulses due to the nature of servo operations, was filtered through an RC circuit. The filtered signal was measured by the ADC function (10 bits resolution, rate = 50/s) of a microcontroller, which also generated command signal to servo. For a given oscillation frequency and amplitude in each measurement, the measured signals in the first 20s were ignored due to the charging process in the RC

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Fig. 3—Experimental setup for average velocity measurements

Fig. 4—Schematic diagram for the measurements of servo power consumption
circuit and other transient effects in hydrodynamic system. The data in the next 60s were collected and averaged. The shunt voltage, and hence the servo current were calculated with the consideration of reference voltage and amplification. The averaged servo power consumption $P_s$ can be obtained accordingly.

**Results**

**Drag Coefficient and Added Mass Determination**

Fig. 5 plots the experimental data (discrete points) for the added mass and drag coefficient determination experiment with different pulling weights. With some manipulations of Eq. 2 and Eq. 3 for data fitting (see for details), the pulley friction, drag coefficient, and added mass are 30.8mN, 0.71, and 685g, respectively. With these parameters substituted in Eq. 2, Fig. 5 also plots the displacement curve for each pulling weight and it can be seen that there is a well agreement between the model in Eq. 1 with solution in Eq. 2 and the experimental results.

**Velocity Measurement and Hydrodynamic Power Dissipation**

Using the values of drag coefficient and added mass obtained previously, the ratio of terminal velocity to the average velocity as computed from Eq. 11 and Eq. 13 is $R_v = 0.69$. Therefore, the terminal velocity can be determined from the average velocity with the relationship $v_\infty = v_a / 0.69$.

Fig. 6 plots the terminal velocity versus the flapping frequency with the best-fit lines (with the constraint of zero y-intercept) for a constant flapping amplitude of 16 degree. The experimental data show that the terminal velocity is proportional to the frequency for all fins. Larger caudal fin produces higher thrust and hence, higher velocity. The highest terminal velocity (=14.1 cm/s) is obtained by using 3825Rect oscillating at 4 Hz. With Eq. 14, Fig. 7 plots the hydrodynamic power dissipation $P_d$ of the fish robot swimming corresponding to Fig. 6.

**Servo Power Consumption Measurement**

Figs. 8, 9 and 10 plot the servo power consumption $P_s$ versus flapping frequency for caudal fin 2025Rect, 2925Rect and 3825Rect respectively. Each caudal fin was oscillating underwater for different flapping frequency (1.5 Hz to 4 Hz) and amplitude ($\theta_{max} = 5^\circ$ to $20^\circ$) during power measurements. Oscillation with
larger fin size and flapping amplitude consumes more power. The results always show a quadratic relationship between the power consumption and flapping frequency for any oscillating amplitude.

Discussions

The fish robot was holding static during the servo power consumption measurements. The situation can be treated as infinite drag on the robot during swimming, and hence, the measurement results yield the upper bound on the power consumption. From the curve fittings in Fig. 8 to 10, the constant terms are due to basic power consumption from the electronic circuit inside the servo, while the quadratic terms indicate that the mechanical friction is proportional to the angular velocity of caudal fin oscillation.

For the ostraciiform fish robot swimming in this research, power is dissipated in two different ways. The power dissipated to hydrodynamic drag is proportional to the cubic of oscillation frequency (as seen in Fig. 7), while the total power dissipations of the actuator shows a quadratic relationship with flapping frequency (as seen in Fig. 8 to 10). It can be seen that the hydrodynamic dissipation is always much less than the other power consumption. Hence, the total power consumption has apparently a quadratic relationship with the flapping frequency.

For a given flapping frequency and amplitude during swimming, the Froude energy efficiency $\eta$ is the ratio of hydrodynamic power dissipation $P_d$ to servo power consumption $P_s$ (i.e. $\eta = P_d / P_s$). Using the results in Fig. 7 and the curves of $\theta_{\text{max}} = 15^\circ$ (which should be close to the power consumption for $\theta_{\text{max}} = 16^\circ$) in Fig. 8 to 10, the energy efficiency of the ostraciform swimming using servo motor is plotted in Fig. 11. The low energy efficiency is due to the dominant power consumption in servo operations and friction caused by mechanical joints, servo gear and waterproofing grease, etc. The fish robot in this research does not imply the low energy efficiency in other ostraciiform fish robots since the mechanical design and choice of actuator play a critical role in the energy efficiency.
The energy efficiency is increased (apparently linear) with flapping frequency for all fins, and larger fin yields a better efficiency as ascribed in Fig. 11. The linear relationship can be deduced from cubic relationship between the useful swimming power (equal to hydrodynamic dissipation) to the frequency and the quadratic relationship between the total power consumption of actuator to the frequency. This suggests that higher percentage of total power is converted into the useful power for swimming at higher frequency. Therefore, the energetically effective way for the ostraciiform swimming is using a larger caudal fin and higher flapping frequency (provided that the servo is strong enough to work against the hydrodynamic drag on fin).

**Conclusion**

In the swimming study of a servo motor actuated ostraciiform fish robot, which achieved the piscine propulsion by caudal fin oscillation, it is found that the terminal velocity is proportional to caudal fin flapping frequency. The hydrodynamics power dissipation increases with the frequency cubically while the servo power consumption, which is much higher than the hydrodynamic power dissipation, exhibits a quadratic relationship with the frequency. Since the hydrodynamic power dissipation is much less than the servo power consumption for any frequency (1.5 Hz to 4.0 Hz) in this study, the total power required for the fish robot swimming is dominated by the quadratic relationship. From the energy efficiency calculations, the ostraciiform robot should utilize a larger caudal fin and higher oscillation frequency for energy efficient swimming.

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**References**