Initial Development and Experiments on a Robotic Fish with a Novel Undulating Fin

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***Abstract*—In this paper, a robotic fish which has a novel fin structure conceived and designed to be as a propulsor is proposed. The ultimate goal of this project is to provide an insight into the methodology of designing and controlling a propulsion system underwater, which is employed at low speeds, offering greater maneuverability, better propulsive efficiency. The whole process of design, construction and control of a prototype is presented; the experiments are performed to study performances of the fin and to verify the feasibility for further development as an alternative propulsion method for underwater vehicles.**

***Keywords*—robotic fish, the undulating fin, propulsor**

I. INTRODUCTION

Fish that involve the use of their median and pectoral fins, termed median and/or paired fin (MPF) locomotion could offer obvious advantages at low speeds, with great maneuverability and high propulsive efficiency, in a cluttered environment [1]. The black ghost knifefish is a remarkably nimble fish and the fish propels itself by oscillating its long fin, thereby producing a traveling wave along the fin, while keeping its thin, flat body mostly rigid [2]. The 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 [3]. Their remarkable abilities could inspire innovative designs to improve the ways that man-made systems are propelled in and interact with the aquatic environment. Therefore, the robotic fish which moves by undulating its long flexible fin will benefit from the fish above and may lead to a good solution in the applications of exploration, inspection and so on in the deep sea.

II. MECHANICAL STRUCTURE

What we desire is to invent a robotic fish that could move by the undulation of the fin and could achieve an ideal performance. So the robotic fish is designed with a three-dimensional model shown in Figure1.

A. *Overall Structure*

In order to realize various movements underwater, the robotic fish is composed of an oscillating guide-bar mechanism for swimming forward/backward, and a swing tail for turning left/right, and a gravity allocation module for going up/down. A traveling wave generated by an oscillating guide-bar mechanism at the head of the robotic fish and passed along a long flexible fin from head to tail could produce the force to propel the robotic fish to swim forward. To swim backward in the water, the traveling wave is generated by an oscillating guide-bar mechanism at the tail of the robotic fish. The gravity allocation module is designed via worm and gear to change the position of the weight and adjust the barycenter of the whole apparatus. The turning movement is achieved while the tail swings to a certain angle by a servo motor to attain enough torque.

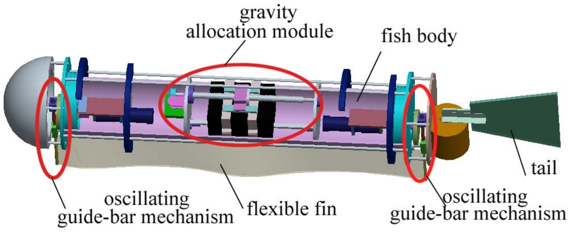


Figure 1. The model of the robotic fish

B. *Undulating Fin Design*

The traditional mechanical fin usually consists of several same fin segments which are driven separately by several same actuators such as servo motors, and it produces the traveling propulsive wave by oscillating fin segments out of phase [4][5][6]. Although this method is able to produce undulations, similar to those produced by actual fins, its structure and control strategy are complicated. We introduce a new way to produce the undulations along the fin in the following part.

1) *Oscillating guide-bar mechanism*

The oscillating guide-bar mechanism is driven by one DC motor A whose angular displacement with respect to axis-x is specified by φ, and the oscillating arm BC whose angular deflection from axis-x is specified by θ can oscillate in certain angles cyclically, so it's possible to produce continuous traveling wave along the fin, as shown in Figure 2.

According to the geometrical relationships of the mechanism in Figure 2, it is obviously described by the following vector expression:

$$\boldsymbol{BA}+\boldsymbol{AC}=\boldsymbol{BC} \tag{1}$$

Therefore, it is obviously to see:

$$l_{BA}e^{i\pi/2} + l_{AC}e^{i\varphi} = l_{BC}e^{i\theta} \tag{2}$$

where l_{BA}, l_{AC} *and* l_{BC} is the length of ***BA, AC*** and ***BC*** respectively. So the variable θ can be calculated as:

$$\theta = \begin{cases} \arctan\dfrac{h+r\sin(\omega t)}{r\cos(\omega t)} & \arctan\dfrac{h+r\sin(\omega t)}{r\cos(\omega t)} > 0 \\ \arctan\dfrac{h+r\sin(\omega t)}{r\cos(\omega t)} + \pi & \arctan\dfrac{h+r\sin(\omega t)}{r\cos(\omega t)} < 0 \end{cases} \tag{3}$$

where ω is the angular velocity of the crank AC, and h and r equal to l_{BA} and l_{AC} respectively. As a result, the maximum oscillating angle $\theta_{\max}$ and the minimum one $\theta_{\min}$ could be obtained from (3). In addition, defining □θ as the difference between $\theta_{\max}$ and $\theta_{\min}$, with different l_{AC}, namely r, different □θ could be obtained. In this project, six different □θ, namely oscillating scope, are designed, respectively to be 23.5°,32.5°, 36.9°, 41.1°, 45.2°, and 49.2°. The results with different □θ will be shown in section IV.

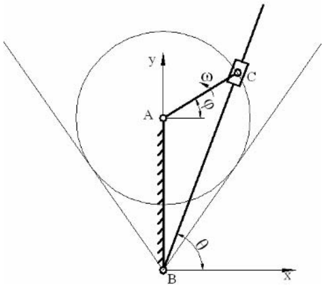


Figure 2. Oscillating guide-bar mechanism

2) *Long undulating fin*

The fin plays an important role in producing a traveling propulsive wave, and it's the premise to determine whether the robotic fish could swim smoothly. The size, shape and material of the fin are all key factors for designing the robotic fin. As mentioned above, one side of the fin is completely fixed to the fish body (short for inner edge), and another side is actuated to transfer the traveling wave (short for outer edge).The length of inner edge is a constant, while the length of outer edge is larger than that of inner edge, so as to producing large amplitude wave along the fin. At the same time, different lengths of outer edges are able to generate different wave amplitudes or different number of waves, illustrated in Figure 3. The material of the fin should be some flexible elastic sheet. Here we choose a 0.2mm thin elastic polyvinyl chloride (PVC) sheet as the fin material.

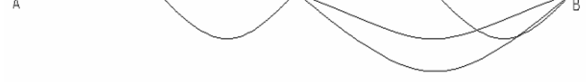


Figure 3. Sketch of producing different amplitudes or number of waves

III. CONTROL SYSTEM

The object of constructing a complete control system is to perform various movements correctly by controlling two DC motors for swimming forward and backward, and a step motor for pitching, as well as a servomotor on the tail for turning. In Figure 4, it is clearly to see that the robotic fish is controlled not only by radio-controlled way, but also by RS232 serial interface to a Windows PC, by which the robotic fish can do corresponding movements in variable velocities by receiving different control commands.

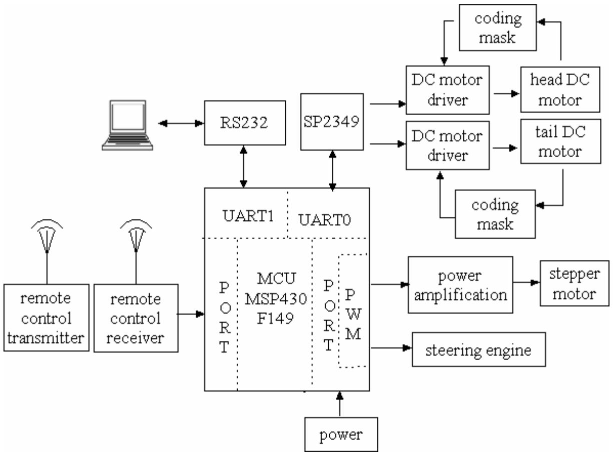


Figure 4. Control system of the robotic fish

IV. INITIAL EXPERIMENTS & RESULTS

A. *Performances of Undulating Fin*

To better design the robotic fin, an experimental setup is designed, as shown in Figure 5. The robotic fish body is fixed on the top of an aquarium (0.80m×0.30m×0.35m) and only the fin is completely immersed in water. A grid of 2.0-cm squares is placed at the bottom of the aquarium and each side of the aquarium is illuminated by one lamp (1000 W). A Canon A620 camera which is located below the aquarium with the shooting rate 30 frame·s-1, is used to film during periods of the fin undulating, as shown in Figure 6. After processing, the films are analysed frame by frame to get experimental data. The experimental results listed in Figure 8 demonstrate the effect of varying the frequency, amplitude and length of the traveling wave on the robotic fin's wave transferring. From section II, we know that varying the amplitude of the wave can be realized through changing the radius of rotation of the slider C in Figure 2. It's easy to change the frequency of the wave just by changing the velocity of the DC motor through setting different control commands in the PC software, while the wavelength needs to be changed by using different size of fins.

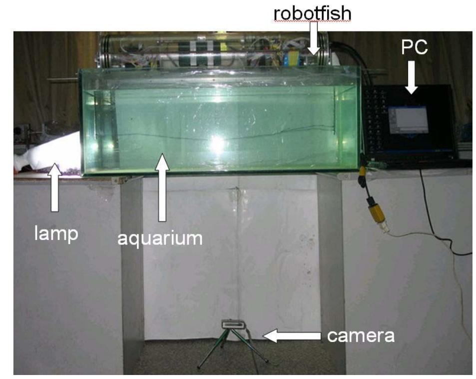


Figure 5. Experimental setup for undulating robotic fin

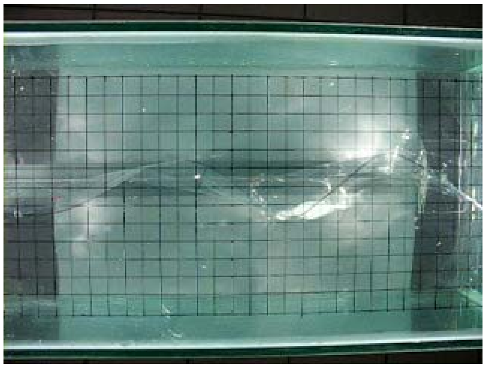


Figure 6. Bottom view of the aquarium

Considering different shapes of the fins, we define the fin in the way "Hs-Hm-He cm", as shown in Figure 7, where Hs, Hm, He respectively mean the width of the fin at the starting point of the fin, at the midpoint of the fin and at the end point of the fin, e.g. "15-20-15cm" means that the width of the fin increases from 15cm to 20cm at the midpoint and then decreases to 15cm till at the endpoint, and "15-20cm" means that along the fin form head to tail, the width of the fin always increases from 15cm to 20cm.

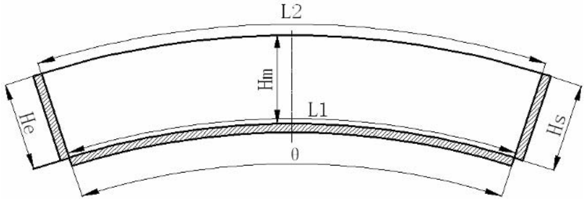
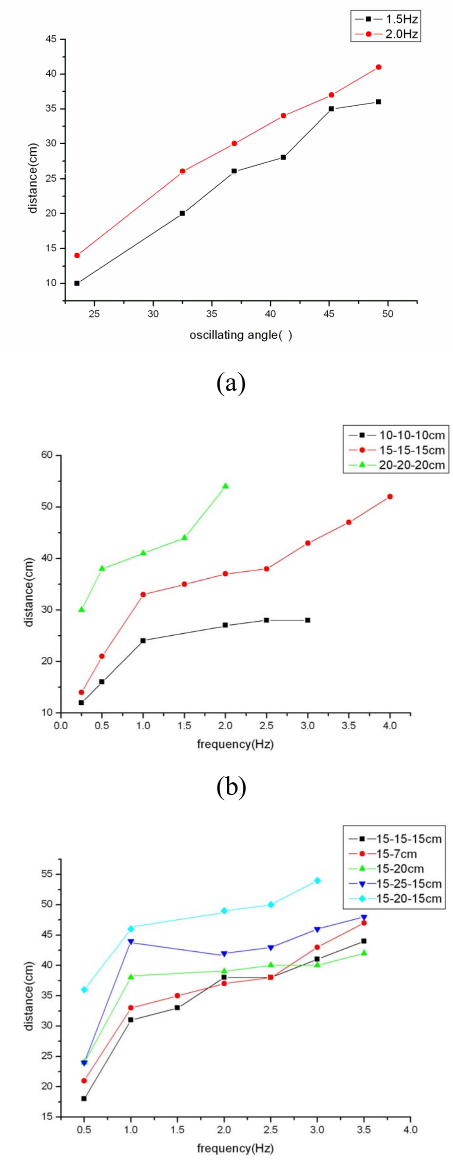


Figure 7. Description of the shape of the robotic fin

Then, the results are given as follows:

- Figure 8.a shows that as the oscillating angle, namely the amplitude of the wave increases, the distance the wave travels along the fin increases linearly. However, when the amplitude is too small, the traveling distance of the wave is very short. So in such circumstances, it's hard to generate enough thrust to propel the robotic fish. The fin sample used in this experiment is "15-15-15cm".
- Figure 8.b shows that the higher the oscillating frequency is, the longer the distance of the wave travels. And this robotic system can work at 4.5Hz to the limit.
- Figure 8.c shows that the traveling distances of the wave with different shapes of the fin are obviously different from each other, and the longer one is the fin "15-20-15 cm". It means that the fin with the shape that the width is narrower toward anterior and posterior is good for the traveling of the propulsive wave.
- Figure 8.d shows that the speed of the traveling wave increases linearly as the oscillating frequency increases.

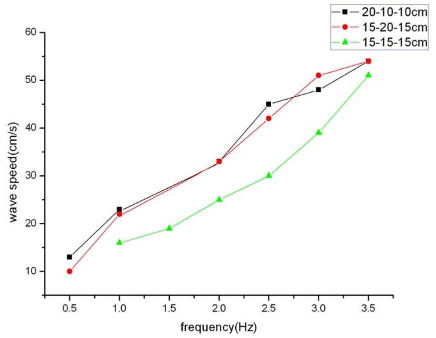
Experiments that showed in Figure8(b), Figure8(c), Figure8(d) use the fin samples with the same oscillating angle △θ 45.2°. In fact, we also do other experiments on the fin and find that as increasing the length of the outer edge of the fin while keeping the inner edge constant, the traveling distance of the wave decreases.



(a)

(b)

(c)



(d)

Figure 8. Experimental results on the robotic fin varying the amplitude, frequency, size, and the shape of the fin.

B. *Motion Experiments*

Since the prototype of the robotic fish is designed and constructed, the experiments have been done in a large water tank (3.5m×2.5m×2.5m) to verify the feasibility of the design and to measure the velocity of swimming forward and backward of the robotic fish. The robotic fish of which the fin is used "15-20-15cm" and the oscillating angle $\triangle\theta$ is 45.2° could swim forward and backward, pitch and turn by setting control command correctly, as shown in Figure9. The measured results detail in Figure10 where positive data are for swimming forward and negative data are for swimming backward.

Figure 9. Movements of the robotic fish: swimming, turning, and pitching

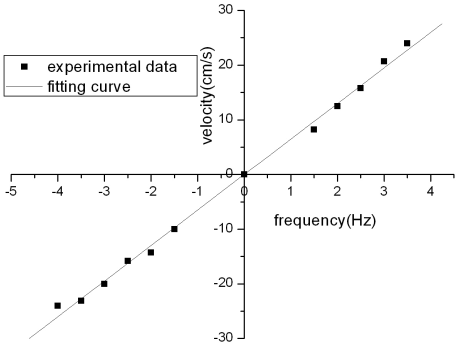


Figure 10. Results of swimming forward and backward in a water tank

V. CONCLUSION

In this research, we are devoted to developing a robotic fish with novel structure of a long flexible fin as the main propulsor for swimming. The methodology of designing a complete prototype of the robotic fish is discussed. In particular, a propulsion system based on a long flexible fin with no fin rays is explored, and proves to have potential application for further underwater vehicles as a possible propulsion method. Future work will be mainly focused on building a more lightweight, compact and nimble robotic fish, and improving the control strategy to be more autonomous and adaptable to various conditions.

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