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Design of a Robotic Fish Propelled by Oscillating Flexible Pectoral Foils

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Abstract— **This paper proposed a new method of designing a flexible biomimetic fish propelled by oscillating flexible pectoral fins. The molding soft body is adopted in the robotic fish. Pneumatic artificial muscles are utilized as driving sources and two ribs with distributed flexibility as main parts of the propulsive mechanism. The leading edge locomotion profile of the flexible pectoral fin in air is studied experimentally, and the flapping locomotion in water is observed too. Finally, the effectiveness of the proposed method is illustrated by the experiment. It shows that the robotic fish can realize self-driven, and it can swim at a speed of 0.18m/s~0.20m/s after optimization.**

I. INTRODUCTION

CONSIDERABLE work has been focused on fishes, for their high velocity, high efficiency and excellent maneuverability are expected properties for man-made under-water vehicles. Many biomimetic prototypes now are propelled by fluctuation body and caudal fins, as considered having higher velocity and efficiency. The pectoral fins are usually used to assist propulsion, improve mobility and control balance.

Many fishes get turning moments by their oscillating pectoral fins which can also help to keep their motion being with high maneuvering capability and excellent stability [1], [2]. Recently, study on elasmobranches shows that fishes with flexible pectoral fins can swim with reduced thrust requirements and increased efficiency as a result of hydrodynamic ground effect and their low energy consumption gliding in water [3]. The efficiency of these fishes is at least as high as the ones driven by fluctuation body or caudal fins. Theoretical and experimental researches on rigid [4] and flexible pectoral fins [5], [6] are becoming more available.

It is experimentally proved that flexibility can reduce resistance, lower noise and increase efficiency of fish [7], [8]. But most of robotic fish with oscillating pectoral foils now are composed by rigid components. Although some fins or joints may have certain flexibility, the effect on propulsive performance is far from sufficient. Some other biomimetic flapping foil robots are simplified as to mimic the motion but not comprehensive in physical structure and locomotion function [9]. The soft-bodied manta swimming robot focusing on the performance of a bending pneumatic rubber actuator was also developed and it can move smoothly in water at a speed of 100mm/s [10].

A flexible bionic fish propelled by oscillating flexible foils, potentially occupies the futures of high efficiency, excellent stability and maneuverable capability. That is the reason the robotic fish in this paper was developed.

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II. NATURE PROTOTYPE

The biological template for the design is cownosed ray, a typical elasmobranch using large flat flexible pectoral fins as the source for propulsion, as shown in Fig.1.

Fig. 1. Cownosed ray (from: http://elasmodiver.com/)

As one of the most efficiency swimmers in the ocean, cownosed rays can migrate over long distance at a speed of 0.6~0.8 times of its body length per second with high efficiency [11].

Cownosed rays swim in a mode called "Mobuliform", characterized by the low flapping frequency, less than half a wave presented on fins at any specific time and the foils never extending below the ventral body axis during the down-stroke [12]. It has been observed that there is only 0.4 full wave presented on foils of cownosed rays, and the flapping frequency is approximately between 0.8~1.4Hz, much lower compared to caudal fins [11].

It is considered to be an ideal creature to imitate in developing a robotic fish utilizes oscillating flexible pectoral foils as the propulsive source, featuring stability and maneuverability.

III. WHOLE-FLEXIBLE BODY DESIGN

The whole-flexible body is designed according to the biological and anatomical results of cownosed ray [11], [13], and made of two-component 8X liquid silicone rubber. The silicone rubber has perfect shear bond strength and secondary concreting compatibility after solidifying.

Optimization of the soft body is achieved through multiple pouring tests. The final whole-flexible body has a wing span of 550mm, a maximal chord length of 330mm, and a maximal vertical section thickness of 65mm, as is shown in Fig.2, which is approximately the same size as a normal cownosed ray. All the vertical sections are approximate to symmetric NACA air foil profiles, as were in Reference [13], changing from NACA0020 at the root to NACA0010 at the wing tip transitionally. The configuration is physically consistent with a cownosed ray, and the effect drawing is shown in Fig.3.

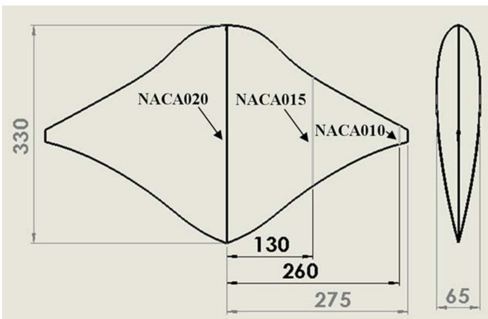

Fig. 2. Dimension of the whole-flexible body

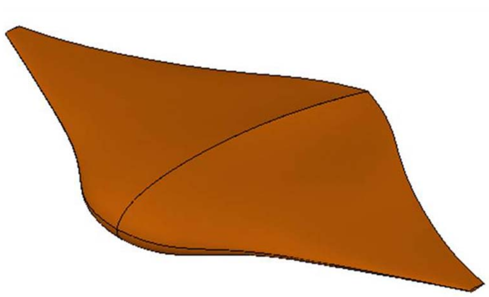
Fig. 3. Effect drawing of the robotic fish


Fig. 4. The right part of the whole-flexible body before dressing, showing with the midsection and the cavity

Wall thickness of the cavity inside the foil, being used to place driving mechanism is changed gradually from 10mm of the vertical midsection to the final 3mm along span wise. This thickness distribution is experimentally verified meeting with the requirements of the foil deformation.

Considered the assembled work, the whole-flexible body is composed of two symmetric parts separated from the vertical midsection, as is shown in Fig.4. These two parts are bonded together with the same silicone rubber after putting the driving mechanism in.

IV. Driving Mechanism Design

The inside driving mechanism consists of three parts: the middle support frame connected to the whole-flexible body, the anterior oscillating mechanism and the reserve posterior direction control part.

Motive power is generated by a self-made pneumatic artificial muscle based on the McKibben actuator [14]. The McKibben muscle has advantages of smooth deformation, high force to weight ratio, and light weight, make it fit for the driving mechanism in this paper. The artificial muscle has a size of 12mm in outer diameter, 220mm in length. The muscle gets 40mm of shortening, under 0.4Mp air pressure, being enough for the symmetric driving deformation.


Fig. 5. The self-made pneumatic artificial muscle

Replication of the fin surface deformation of the cownosed ray is difficult now, for the fin-surface shape during flapping is very complicated. So skeletons of cownosed ray are simplified to an oscillating skeleton put inside the leading edge, and its deformation is actively controlled. Expected accurate leading edge motion deformation is achieved by controlling on flexibility distribution of the soft body and the ribs. Other parts of each foil get passive deformation under flow action during oscillating.

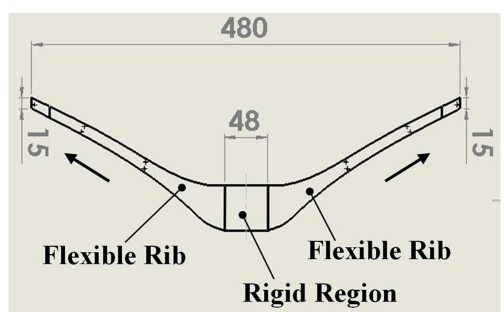

Fig. 6. The Skelton with distributed flexibility

The oscillating skeleton has three regions: the middle rigid region, the left flexible rib and the right flexible rib, as is shown in Fig.6. The rigid region is threaded connected to the rigid backbone of the middle support frame. The two elastic ribs with distributed flexibility are bilateral symmetry and made of fiber sheet in different stiffness and thickness. According to the driving requirements, thickness of each rib is thinning out along the own arrow direction, as shown in Fig.6, also the rib rigidity, but not linearly. The anterior edge profile of the oscillating skeleton is the same as the leading edge of the flexible body.

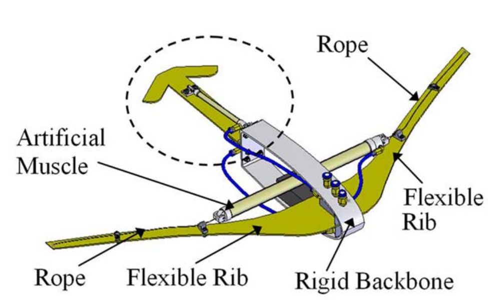

Fig.7. The inside propulsion system

The driving principle is simple. When the air pressure is increased in the internal expandable chamber of the artificial muscle, the muscle will contract and produce tension, then the ropes both on left and right will move towards the midsection, and the flexible ribs will get an elastic upstroke deformation along the leading edge. Finally, the soft pectoral fins will get a similar oscillating deformation driven by the ribs.

The enclosed part by elliptic dash line in Fig.7 is reserve direction control mechanism needed as only symmetric flapping locomotion can be achieved for the one artificial muscle driving in the frontier in this preliminary prototype. This mechanism is not detailed discussed in this paper, for it is not experimentally studied yet, although equipped.

V. ROBOTIC FISH

The robotic fish is assembled after the flexible body and the driving mechanism being built. It has a high degree of similarity with cownosed ray in physical morphology, as is shown in Fig.8.


Fig. 8. The flexible robotic fish with the soft air tube

Driving mechanism is put into the flexible body as a whole. Middle seam between the two symmetric foils are sealed by double-layer 8X silicone rubber in order to guarantee the isolation from water. The driving compressed air is provided through a soft air tube connected to the outside proportional controlled compressed air source.

The robotic fish density is less than water, and a counterbalance of 1.52 kg is needed to keep it submerged floating, as is shown in Fig.9. The bionic fish has excellent waterproof property, and there is no water leakage phenomenon during a fifteen days under-water experiment.

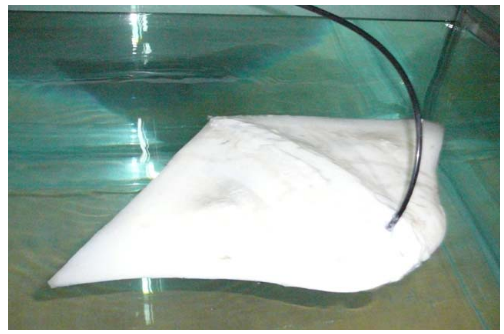
Fig. 9. The robotic fish suspension in a water tank

VI. PRELIMINARY TEST

A. Foil Deformation

The leading edge locomotion profile seen from the anterior view during an up-stroke cycle is studied experimentally, and is consistent well with the result given by Reference [11].

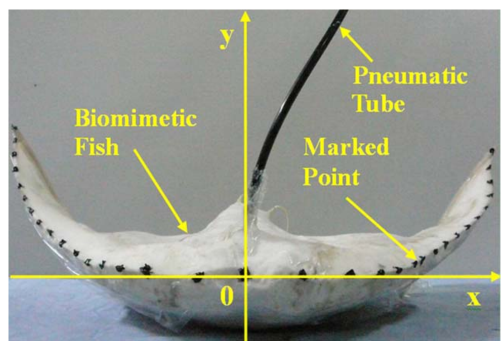

Fig. 10. A screen snatch of wing deformation with the coordinate system

Mark points are drawn on the leading edge, in order to clearly determine the foil curvature during the up-stroke circle in the snatch screen. Coordinate system is settled as shown in Fig.10. The origin point is set on the anterior vertices, and x-axis is paralleled with the lateral body axis, y-axis with dorsal ventral body axis. Coordinate values of the mark points are measured, both during an upstroke cycle and at static state. The mark points are not in standard shape, so the geometric center is used in the measurement. Three values for each mark point at each time step are measured, and the average is taken.

The accurate leading edge deformation of this robotic fish corresponding to a specific time step during a flapping circle can be adjusted through the proportional controlled air source. And the flapping frequency is set to 1Hz in the test.

Each line of Fig.11, based on the measured coordinate data, represents the leading edge profile seen from the anterior view of the left pectoral fin at a different time, at a 2/30 sec interval, during an upstroke cycle, except the bottom one of static state.

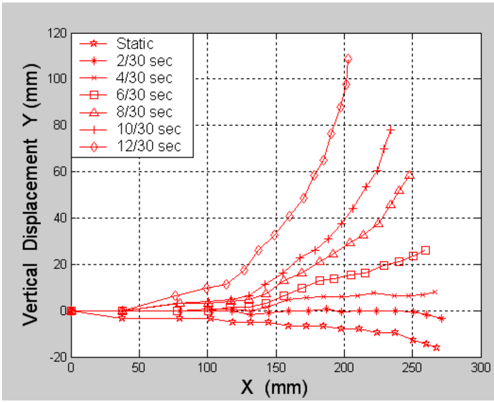

Fig. 11. Leading edge profile seen from the anterior during an upstroke circle and at static state

The wing curve is almost below x-axis and the wing tip has the maximum of 18mm, under gravity at static state. The highest oscillation amplitude of the left fin is 110mm, which is about 0.2 times of the wing span. Middle part of the flexible body, about 40% of the wing span, is under less deformation, as a cownosed ray.

Motion deformation of the foils during a flapping circle in water is observed too, as shown in Fig.12. The flapping amplitude is smaller than that in air, under water resistance. The swimming robot moves smoothly in water like a living cownosed ray.

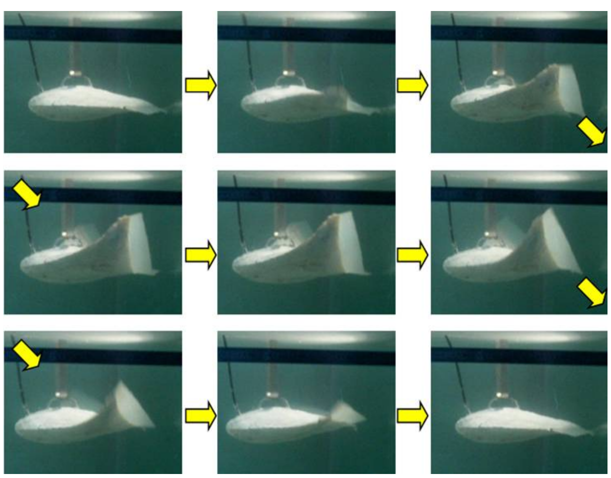
Fig. 12. An oscillating circle in water

B. *Linear Velocity*

A testing platform is designed to study whether the robotic fish can propel itself and the linear swimming velocity. As shown in Fig.13, the platform is consisting of a linear guide, a hanger frame and a ruler. Upper tip of the hanger frame is connected to a slider of the linear guide, and the lower end to the robotic fish. The fish and the lower part of the hanger frame are put into a still water tank. Friction of the linear guide is neglected here. So the restricted linear velocity can be achieved and investigated.

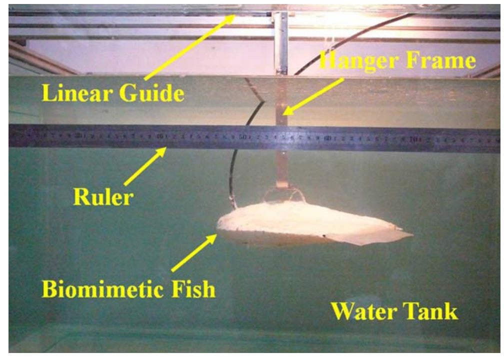

Fig. 13. The linear velocity test platform

The robot fish can realize well self-driven, but the linear velocity is only about 0.10m/s, not as fast as expected. It is found mainly causing by the redundant trailing edge rigidity, which makes the posterior deformation of the foil less than need. Then a narrow slip of soft silicone rubber board is attached to the trailing edge to optimize it.

The optimized robotic fish can swim in water with a velocity of 0.18m/s~0.20m/s, approximately 0.5 to 0.6 times of its body length per second.

VII. CONCLUSION

This paper applies the preliminary design and experimental work of a flexible biomimetic fish with distributed flexibility structure. Design of the flexible body and the driving mechanism was presented, and the related experimental work is discussed. The presented robotic fish has a leading edge deformation and can swim softly in water similarly to a cownosed ray. It can realize self-driven. Although the velocity is not as fast as expected, the main reason is found and preliminary improvement is done. Propulsive performance of the robotic fish will be further tested.

Optimization design is under processing, and a new bionic fish propelled by active control pectoral foils, each with five flexible oscillating skeletons, will be developed in the near future. Propulsive performance of pectoral foils with distributed flexibility will be studied both theoretically and experimentally as the flexibility distribution changes.

VIII. ACKNOWLEDGMENT

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