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Design and implication of a bionic pectoral fin imitating cow-nosed ray

Yueri Cai, Shusheng Bi, and Lige Zhang

Abstract—**Pectoral foil structure and motion discipline of cow-nosed ray as nature prototype is analyzed. A bionic pectoral fin is designed according to the analysis results. Propulsion performance of the bionic fin at sinusoidal motion law is studied experimentally on a towing platform, at the oscillating frequency from 0.2 Hz to 2 Hz and amplitude from 2.5° to 30°. Well driving ability is obtained, and maximal average thrust of 2.75N is achieved by a single bionic fin expressed at towing speed of 10 cm/s. A biomimetic fish utilizing the kind of bionic fin is developed, and swimming speed of 0.9BL (body length) in maximum can be reached.**

I. INTRODUCTION

PECTORAL foils are usually utilized to balance body, control direction, and brake for a swimming fish [1], and they are critical for improving swimming maneuverability. High maneuverability was shown by some bionic fish propelled by paired pectoral foils, also higher velocity and efficiency [2].

The cow-nosed ray is a typical one utilizing two oscillating pectoral foils for propulsion. It has several characteristics that attract us to consider it as an ideal nature prototype for designing a bionic foil and further a robotic fish, such as compact, efficiency, and maneuverability. The paired pectoral foils are main thrust source for their driving, turning, gliding and keeping their motion being with maneuverability and stability. It is relatively simple to realize a man-made one according to them. Also, higher efficiency and velocity were occupied by their flapping motion than fluctuating motion of other elasmobranches [3], which can also be proved by their well known long migrations.

Importance of pectoral foils in designing of bionic fish has been realized by researchers worldwide. There are more and more studies on pectoral foils, not restricted in using as auxiliary driving mechanism, but more as sole source of driving. Rigid pectoral foils featuring with complicated motion of rowing, flapping and feathering and bionic fish related are developed [4], [5]. Flexible pectoral foils with complicated motion are also studied [6], [7], feasibility of applying them to design of bionic fish is proved. Also preliminary development of ray-like prototype are appeared [8]-[12], although the propulsive performance need to be further improved.

Pectoral foil structure and motion discipline of cow-nosed ray are analyzed in this paper. Design of a bionic fin replicating some main features of the pectoral foil of cow-nosed ray is expressed. Thrust generated of the fin is tested on a towing platform. A bionic fish utilizing the same kind of pectoral as the fin designed is illustrated too.

II. PECTORAL FOIL OF COW-NOSED RAY

A. Structure

Cow-nosed ray has flattened and streamlined body, and features of large pectoral foils. Top view of a cow-nosed ray is showed in Fig. 1. Body of cow-nosed ray can be divided into three parts according to the degree of deformation during its swimming, although there are no obvious boundaries. As shown in Fig. 1, the left foil, the right foil and the middle body. The part analyzed in this paper is the left pectoral fin or the right one, which has almost the largest oscillating amplitude among elasmobranches and generates the main forward thrust during swimming.

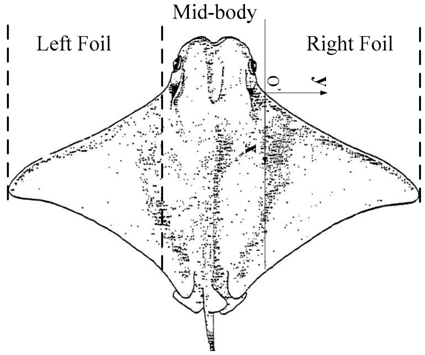

Fig. 1. Top view of cow-nosed ray (modified from reference [13])

As the body of cow-nosed ray is symmetrical, the right foil is taken as the research object. Several platform figures of cow-nosed ray were found and analyzed. Coordinate system is settled as shown in Fig. 1. The origin point is set on the leading edge about 0.14 times of wingspan away from the mid-chord section, which is obtained from analysis of several cow-nosed ray free swimming in marine museum. Coordinate values of the right body edge are measured, as the numerical value figure is shown in Fig. 2. In the figure, the chord length in x-direction from the origin point is set as one length unit. Outer contour of the bionic fin expressed in this paper is

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designed according to scaling up of the numerical results.

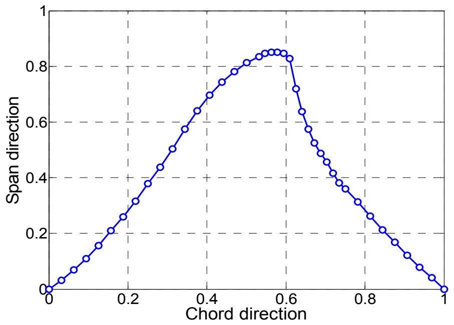


Fig. 2. Dimension value chart of the right foil

Skeleton structure of a kind of elasmobranches [14] is shown in Fig. 3. Red areas indicate calcification bone, and blue is cartilage. The leading edge flexibility is increasing from the mid-chord section to the wing tip and the chordwise rigidity decreasing from the anterior edge to the posterior, as shown by the arrow direction in Fig. 3. Skeleton of cow-nosed ray is similar with it.

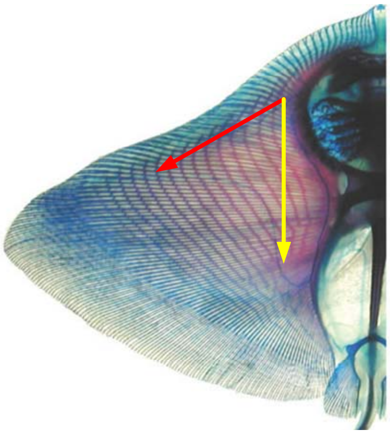


Fig. 3. Skelton flexibility distribution of Gymnura marmorata (modified from reference [14])

B. *Motion Discipline*

Swimming of cow-nosed ray is classified as a type of lift-based type of motion [15] named “Mobuliform” [16]. This mode of swimming generates thrust force by up and down motion of the fin, and the flapping motion is perpendicular to the forward direction.

Videos of free swimming cow-nosed rays in a marine museum were get and the foil deformation was analyzed. The leading edge and posterior edge deformation curves, from lateral view, during down-stroke of a cow-nosed ray are shown in Fig. 4. Time interval between each two contiguous cures is 1/15s. In the figure, the coordinate system is set the same as in Fig. 1, and the z axis is defined according to the right-hand screw rule. It can be observed from this kind of analysis results that there are only about 0.4 full waves presented on their pectoral foils at any specific time during swimming. The flapping frequency range is narrow, from 0.5 Hz to 1.2 Hz. The waves on the foil transmits on two directions, one is from the wing root to the wing tip at the spanwise direction, and the other is from head to tail at the chordwise direction.

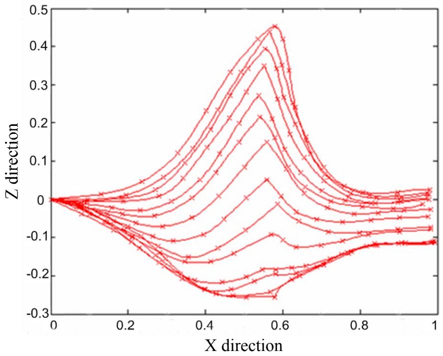


Fig. 4 Leading edge and posterior edge curves during down-stroke

The wing tip motion curve at rear view of one cow-nosed ray is shown in Fig. 5. Sinusoidal motion discipline can be achieved from it. Analyses of different cow-nosed rays come to the similar results.

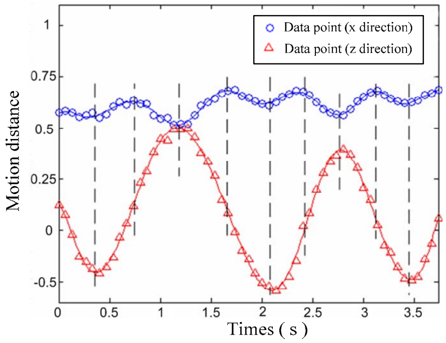


Fig. 5. Wing tip trajectory of a cow-nosed ray

The foil deformation of cow-nosed ray during flapping is relatively simple compared with other auxiliary or undulation ones. It is relatively easier to build a bionic fin and further a biomimetic fish imitating it.

III. BIONIC FIN DESIGN

Flexibility distribution of pectoral foils of cow-nosed ray is complicated, also the foil surface deformation during oscillating. The structure and motion should be simplified in bionic design for it is too difficult to completely replicate them.

Pectoral foil oscillating of cow-nosed ray can be simplified to combination of two kinds of motion: pitching and translation up and down, the same as described in reference [17] and shown in Fig. 6. The translation displacement h_A and the pitching angle α_A can be described as follows:

$$h_A(t) = h_0 \sin \omega t \tag{1}$$

$$\alpha_A(t) = \alpha_0 \sin(\omega t + \varphi) \tag{2}$$

Where ω is the angular velocity of oscillating and φ is the phase difference.

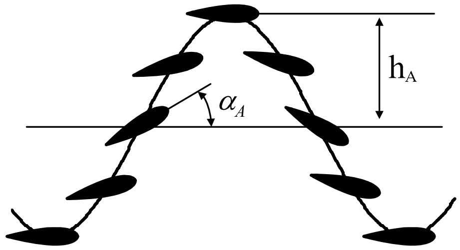
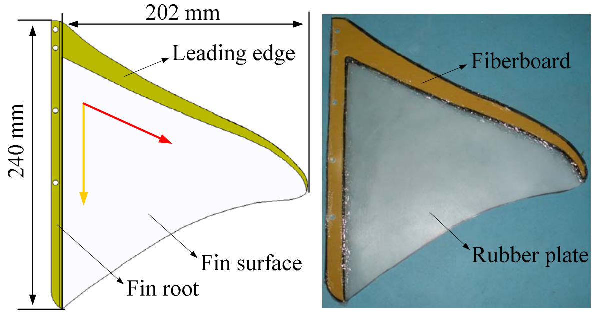


Fig. 6. Simplified model of foil motion

Main structure and motion features of pectoral foil of cow-nosed ray can be realized by a fin with leading edge of distributed flexibility and other fin surface flexible. Effect drawing of the bionic pectoral fin is shown in Fig. 7.A. Size of the fin is similar as the one of an immature cow-nosed ray in nature. Curve shape of the leading edge and the posterior edge are exactly according to the scale model of the results shown in Fig. 2. Leading edge of the fin is made of 2 mm thick fiberboard and fin root of 3 mm. The fin surface is constructed with rubber plate of 2 mm thick. They are bonding together with the D09 adhesive. Width of the leading edge becomes narrow gradually along the direction from the wing root of 30 mm to the wing tip of 2 mm. The spanwise flexibility is increasing along the red narrow direction, shown in Fig. 7.A, realized by this structure. The chordwise rigidity is decreasing along the yellow narrow direction for interaction of the leading edge, the fin root, and flexibility of the material used for fin surface. The actual bionic fin developed is shown in Fig. 7.B.



A. Effect drawing B. Actual photo

Fig. 7. Design of the bionic pectoral fin

Complicated foil motion of cow-nosed ray is simplified to composition of active leading edge oscillating and other parts flapping passively under hydrodynamic force. So, the three-dimensional deformation of the nature foil is approximatively realized by the one-dimensional active oscillating of the bionic one.

IV. TESTING PLATFORM

In order to verify the thrust generated by the bionic fin in swimming, a towing-testing platform is designed, as shown in Fig. 8. Towing speed is provided by the synchronous belt towing mechanism. Sinusoidal motion of the oscillating motor is exactly transformed to the bionic fin by the double four-bar transmission mechanism. Motion curve of the bionic fin is traced by a potentiometer with precision of 0.5%, fixed on the output shaft. Instantaneous thrust changing with time is measured by the torque sensor HK-710.

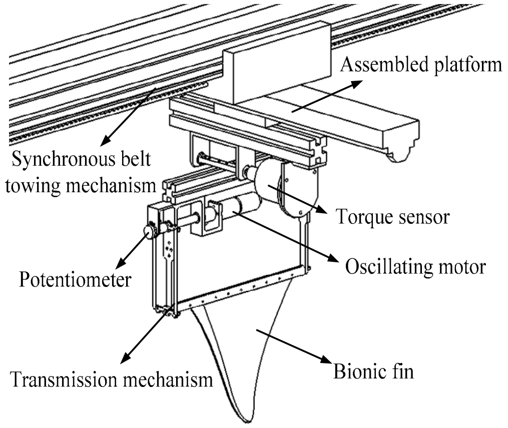


Fig. 8. Schematic diagram of the tow- testing platform

System diagram of the testing platform is shown in Fig. 9. The towing motor and the oscillating motor are both controlled by the PC utilized, through two separated control circuits. Volt signals of the torque sensor and the potentiometer are analog-digital converted by the NI-DAQ 6016, and finally recorded by the PC.

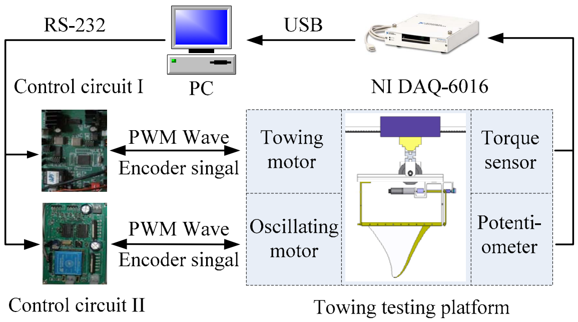


Fig. 9. System diagram of the tow-testing platform

V. EXPERIMENT RESULTS

A. Fin Motion and Instantaneous thrust

The accurate control of bionic fin sinusoidal motion is foundation of the experiments. Actual motion of the bionic fin tracked by the potentiometer is analyzed. The flapping amplitude utilized here is 30° and frequency from 0.2 Hz to 2 Hz, at intervals of 0.2 Hz. Results of the actual motion are consistent well with the sinusoidal discipline under the closed-loop control, except some peak parts with a little flat caused by the clearance of the mechanism, which has little influence on the thrust produced for the short time lasted. The amplitude is becoming smaller as the oscillating frequency increasing, under water resistance. Results of the motion tracking and real-time thrust are shown in Fig. 10.

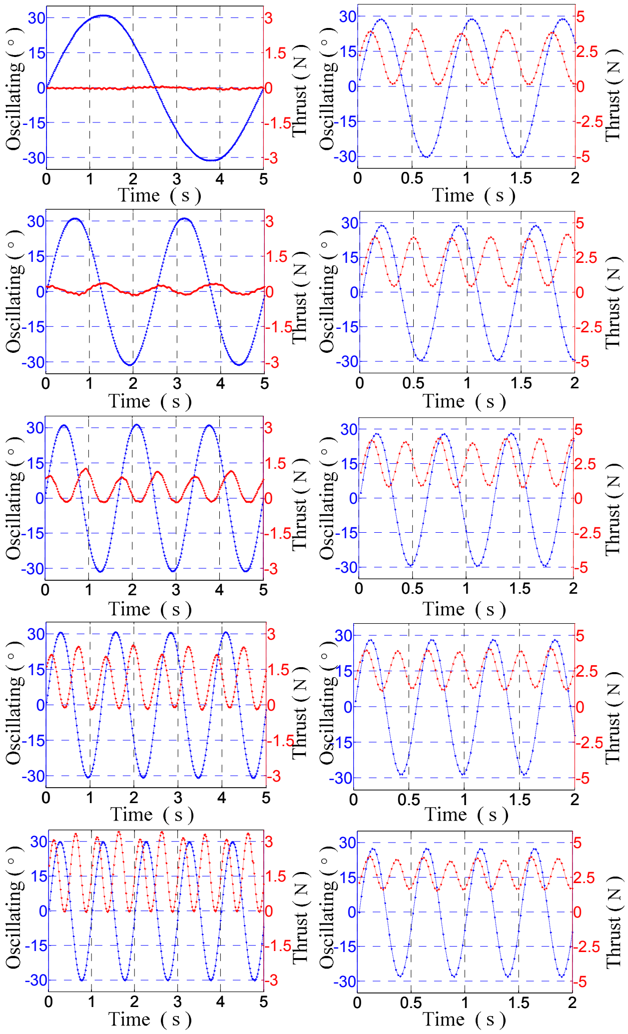


Fig. 10. Sinusoidal motion tracking and the real-time thrust

The real-time thrust produced follows the sinusoidal law. There are two peak values of thrust in a full flapping cycle. Phase difference between the thrust and the motion is becoming small, as the oscillating frequency increased. The maximal instantaneous thrust of 4.35N is obtained at oscillating frequency of 1.6 Hz.

B. *Average Thrust*

Propulsion performance of the bionic fin is tested at towing speed of 10 cm/s. The amplitude utilized varies from 2.5° to 30°, at 2.5° intervals. The oscillating frequency used from 0.2 Hz to 2 Hz, little larger range compared with the swimming frequency of cow-nosed ray. Results of average thrust produced are shown in Fig. 11. The thrust is becoming larger as the flapping amplitude and the frequency increased. But the growth rate of the average thrust is getting smaller at the same time. Impact of the flapping amplitude is becoming greater as the frequency getting higher. This indicates that there must be an optimal combination of flapping amplitude and frequency which can generate the maximum average thrust [18]. The optimal combination varies with the foil structure and motion discipline. For the pectoral foil expressed in this paper, it does not appear in the testing range.

The maximum average thrust obtained in the experiment is 2.75N, at oscillating frequency of 2 Hz and amplitude of 30°. A pectoral foil in the same scale, which has a quarter ellipse shape was developed before [9]. The maximal thrust generated by it is about 0.8 N in experiments, at flapping frequency of 0.8 Hz, and amplitude of 40°. Also, a robotic fish is designed, with a wing span of 0.7m and a body length of 0.5m, based on the quarter ellipse foil. The prototype is almost in the same scale as the one expressed in this paper. The thrust generated by the quarter ellipse foil was large enough to drive the robotic fish. It is obviously that the average thrust generated is enough to drive a bionic fish, using this kind of pectoral foil.

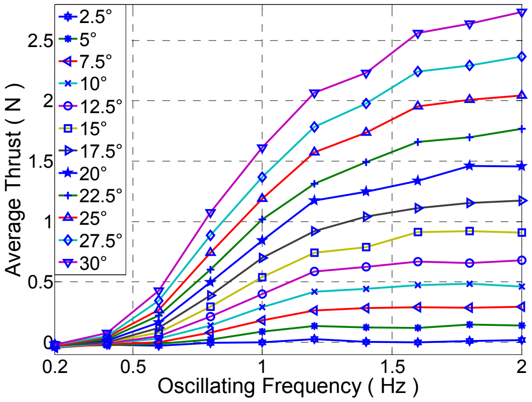


Fig. 11. Average thrust produced by the single bionic fin at series of flapping amplitude and frequency

C. *Bionic Fish*

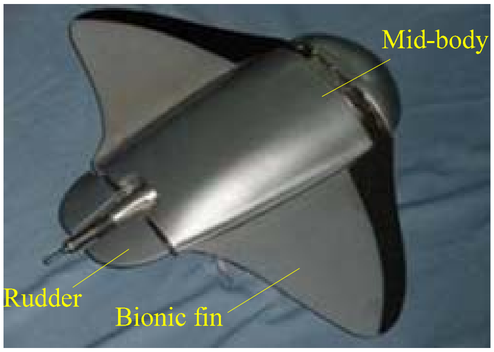


Fig. 12. The bionic fish utilizing the kind of bionic fin expressed

A biomimetic fish utilizing this kind of pectoral fin is developed, as shown in Fig. 12. Rigid mid-body of the bionic fish is made of fiberglass based on the mid-body shape of cow-nosed ray. The paired pectoral foils are constructed according to the bionic fin expressed in this paper. Top view of the bionic fish is similar with a cow-nosed ray, also shape of the mid-body. It has a wing-span of 0.62m, body length of 0.4m, and tonnage of 3.5 kg. The body scale is similar to an immature cow-nosed ray, considering the machining work and the subsequent experimental work.

The two bionic pectoral fins are driven by two separated direct-current motor. Pitching motion of the bionic fish is obtained by the elevator driven by a steering gear, mounted at the posterior part of the mid-body, as shown in Fig. 12. Turning motion is realized by the corporation of the rudder added after optimization and the differential flapping of the two pectoral foils. The rudder can not be seen in Fig. 12, for it is on the other side of the rigid body. At first, the robotic fish was designed to reach turning motion by differential flapping of the pectoral foils, but the performance is not as well as we thought.

Well swimming performance is realized by the bionic fish. The free linear swimming speed is tested in a swimming pool. As shown in Fig. 13, two white lines were set at a distance of 2m. The robotic fish is controlled to swim linearly between the two lines. The swim condition is recorded by a camera, and then the videos were analyzed screenshot by screenshot. Velocity of 0.9BL in maximum is reached by the prototype.

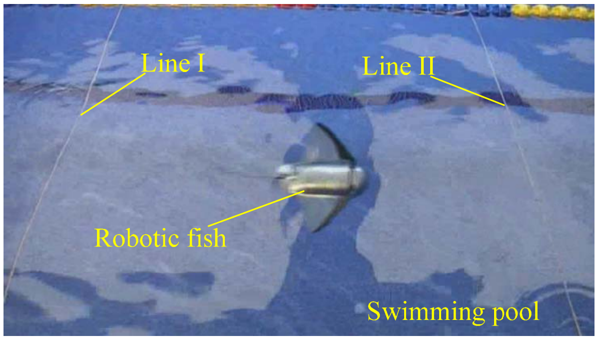


Fig. 13. Velocity test in a swimming pool

VI. CONCLUSION

The structure and motion discipline of cow-nosed ray, including the foil shape, flexibility distribution and motion discipline, are detailed discussed. A bionic pectoral fin imitating main features of cow-nosed ray pectoral foil is developed. Flexible material including fiberboard and rubber plate is utilized for constructing of the pectoral fin. Characteristic of the bionic fin is consistent well with the nature one both in plan-form shape and flexibility distribution.

The bionic fin is competent for being utilized in a bionic fish, which is validated by experiments on a towing-testing platform. As large as 2.75N of average thrust can be reached by a single bionic fin designed. A bionic fish featuring with rigid body and paired flexible oscillating fin is developed based on the bionic fin expressed. Free swimming speed of 0.9BL can be reached by the bionic fish.

Further studies of the bionic fin, such as research on the driving thrust at varies of towing speed and the propulsion efficiency will be carried on to execution. Optimization of the bionic fin based on the experimental results, including the material, the structure and the flexibility distribution, will also be considered, for replication of the nature pectoral foil is not always optimal for a man-made one. Test and improvement of swim speed and maneuverability of the bionic fish expressed need to be carried out too.

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