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A Novel Double-Hull Boat with Biomimetic Wire-Driven Flapping Propulsors

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***Abstract*—This paper presents a novel double-hull boat with two wire-driven flapping propulsors. The boat comprises two identical hulls and a control center. Each hull is propelled by a biomimetic wire-driven flapping propulsor, which has seven joints, and is driven by one servo motor. Propulsion model of the boat is developed by integrating the reaction force during the flapping cycle. Motion of the boat is studied, including cruising and turning around. Two cruising modes and three turning modes are presented. Results show that the boat cruises forward steadily. In the tests, the maximum speed of the boat is 0.323 BL/s; the minimum turning radius of the boat is 0.517 BL; the maximum turning speed is 13.9°/s.**

I. Introduction

Boat is crucial in water transportation, including both ferry and freighter. All around the world, 90% of world trade is carried by water transportation [1]. In the history, boat was propelled by oar, barge pole, wind, paddle wheel, and screw propeller. Most of the propulsion methods are inspired by the aquatics, such as the oar and paddle wheel. Each revolution in boat propulsion had huge impact on human society. It is hard to imagine that without the screw propeller how the shipping industry would be. It is very compact, can yield large thrust, and is ease of control. However, the screw propeller also has its own drawbacks, such as low efficiency and noisy. Also, the turning radius of a boat with screw propellers is large. Compared to fish, ships are still far behind.

People have been mimicking fish in developing fish-like vehicle or robotic fish for two decades since the robot tuna in 1994 [2]. Some well-known fish-like robots are the Essex Robotic fish [3], the SPC-II developed in Beihang University [4], the CAS robotic fish [5], the Tai-robot-kun [6], the Firo [7], etc. All these robotic fishes shows the fish-like flapping propulsion has high efficiency (>60%), low noise, and provides the robot good maneuverability. These robotic fishes all have one flapping tail. During the flapping cycle, besides the thrust an additional lateral force is also produced. This will make the fish body sway along with the tail flapping during swimming. The body swaying makes the swimming unstable and impairs the propulsion efficiency.

Attempts are also made to apply the fish-like flapping propulsion to boat development, such as the fin propulsion boat [8] and the penguin boat developed in MIT in 1997 [9]. For the fin propulsion boat, a single oscillatory paddle is used to propel the boat. Therefore, similar to the above robotic fishes, the boat will sway during the cruising. Also, the paddle oscillation is far unlike the fish oscillating. It is more like using an oar to propel the boat. The penguin boat was tested in the Charles River in 1997. It has a single hull and two flippers. The two flippers oscillate in an opposite manner and can propel the boat forward effectively. However, detailed data was not available and turning performance is not presented. Also, the flippers mimic the penguin motion. They are rigid, which is unlike the flexible fish tail.

Most of the boats or ships have a single hull. However, in recent years double hull design is becoming more and more popular, especially in ferry boat design. The double hull boat has two identical hulls. Each hull has a propeller. Compared to single hull boat, it has a wider deck, larger capacity, and the boat is more steady in cruising [10]. Also, the spacing distance of the two propellers enables the double hull boat turning around with a smaller radius.

The biomimetic wire-driven mechanism (WDM) [11-18] follows animal, such as fish, musculoskeletal system. It has been demonstrated to be well suited to fish-like flapping propulsion. In this paper, a double hull boat with wire-driven flapping propulsors is designed and prototyped. It has two identical hulls, and each hull is driven by an oscillatory wire-driven flapping propulsor.

The rest of the paper is organized as follows. Section II presents the double-hull boat design; section III shows the propulsion model; section IV gives the motion control scheme; section V presents the prototype and experiment validation; at last, section VI gives the conclusion.

II. Double-Hull Boat Design

The double-hull boat comprises two identical hulls, which are driven by an oscillatory wire-driven flapping propulsor each. The two hulls are connected by a central platform, which is also the control center. The following presents the double hull boat design: at first is the flapping propulsor design and followed by the boat layout.

A. Oscillatory Wire-Driven Flapping Propulsor Design

The wire-driven mechanism is demonstrated be well suited to robotic fish propulsion [11, 14-16], including oscillatory form and undulatory form propulsion. It is simple in structure and highly efficient. Both robotic fish and boat are vehicles in water. Hence, the wire-driven flapping propulsor can also be applied to boat design. In the double hull boat, two identical

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wire-driven flapping propulsors are used. The propulsor is designed as in Fig. 1. The propulsor is composed of seven vertebras, a caudal fin plate, a pair of wires, a drum wheel, and several pulleys. The vertebras have a similar structure. Fig. 1 (a) shows one vertebra in the propulsor. As shown in the figure, the cross section is ellipsoid, with a slot at the top and bottom respectively. The slots are used to fix the caudal fin plate. Each end of the vertebra has a semi-circle stage. The vertebras are connected serially. Two adjacent vertebras form a revolute joint by the semi-circle stage. The propulsor is as in Fig. 1 (b). It has seven vertebras. A caudal fin is fixed to all the vertebras via the slots. It has a lunate shape at the end. The wire routing is as shown in the figure. A pair of wires passes by all the vertebras and is fastened to the seventh vertebra. They are guided by the pulleys. The other end of the wire is connected to a drum wheel. With the reciprocal rotation of the drum wheel, the wires pull the propulsor flap side to side. In the design, each propulsor contains only one pair of wires, hence, the flapping motion of the propulsor is oscillatory.

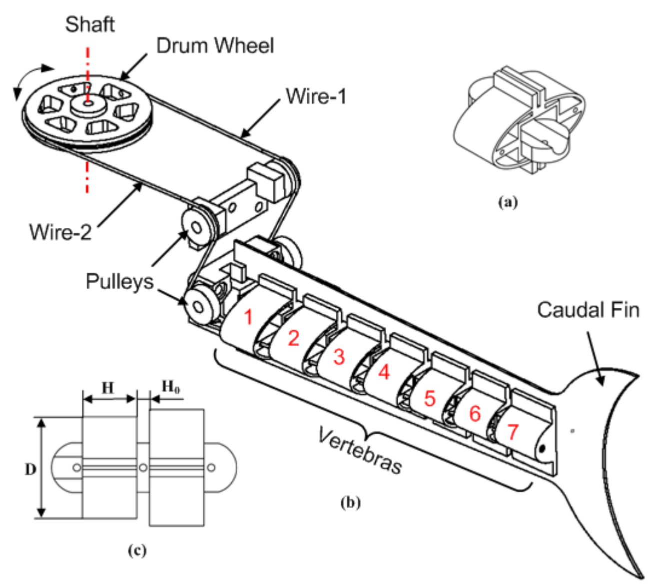

Fig. 1 Wire-Driven Flapping Propulsor: (a) vertebra; (b) wire-driven flapping propulsor and the wire routing; (c) joint in the propulsor

As shown in Fig. 1 (b), the vertebras have similar structures and the sizes shrink from vertebra 1 to vertebra 7. The dimensions are as in Table I. The maximum rotation of each joint is calculated as in [12, 13]. For the propulsor, the maximum flapping angle is 92.16°.

Table I Vertebra Parameters

Num.	H	H_0	D	θ_{max}
1	15	2.5	36	7.94
2	15	5	40	14.25
3	15	4.5	36	14.25
4	15	4	32	14.25
5	15	3.5	28	14.25
6	15	3	24	14.25
7	18	2.5	22	12.97

B. *Double-Hull Boat Design*

The double hull boat layout is as shown in Fig. 2. It comprises two identical hulls; each hull is actuated by an oscillatory wire-driven flapping propulsor. The hull contains the actuator. It also serves as the base of the propulsor. The front of the hull is parabolic, which can reduce the water drag during cruising. The two hulls are connected by the central platform. The spacing distance between the hulls can be adjusted by the platform width. To avoid caudal fin collision, the minimal platform width is 2/π propulsor length. The central platform is also the control center. It contains the power supply, i.e. the main battery and auxiliary battery, the communication unit and the controller.

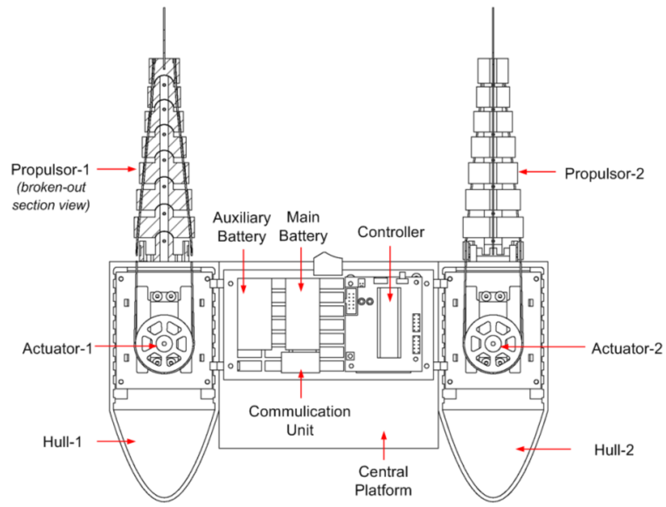

Fig. 2 Wire-Driven Double Hull Boat Layout

The caudal fins should be fully merged into water all the time in order to gain a large thrust. Hence, the propulsors are mounted at the bottom of the hulls. The hulls and control center are all covered with a lid. This can protect the electronics in the boat from the water. Fig. 3 shows the isometric view of the designed double hull boat.

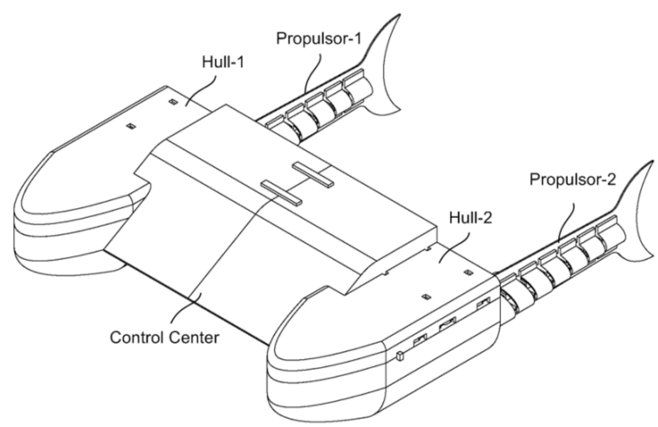

Fig. 3 Wire-Driven Double Hull Boat

III. Propulsion Model

For wire-driven robotic fish, the body is slender, therefore, Lighthill's Elongated Body Theory (EBT) can well predict the robot performance [11, 14-16, 19]. However, the double hull boat is wide and short. Hence, the EBT is not directly applicable. In this section, a propulsion model for the double hull boat is developed. It is based on the reactive force from the water during the propulsor flapping.

When the boat is moving on the water surface, it suffers four types of forces. One is gravity, the second is buoyance, the third is drag force and the last is thrust. Gravity and buoyance balance each other, hence, in the modeling, only the drag and thrust are considered. Fig. 4 shows the drag force and thrust acting on the boat.

From the figure, the drag force acted on the boat is:

$$F_{d1} = F_{d2} = \frac{1}{2} C_d \rho S U^2 \tag{1}$$

where, C_d is the drag coefficient. For the boat, the front shape of the hull is semi-sphere and the bottom part of the control center is in the water, C_d can be chosen as 0.5; ρ is water density; S is the wetted cross-section area of a single hull; and U is the boat cruising speed.

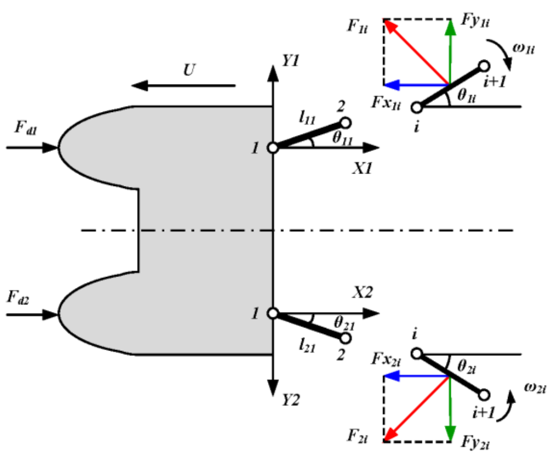

Fig. 4 Drag and Thrust acted on the Double Hull Boat

Thrust is generated by the two propulsors. Each propulsor has identical flapping motion, hence, generating the same thrust. When the propulsor flaps side to side, the reactive force acted on the vertebras is as shown in Fig. 4. The force is decomposed to the X direction (moving direction) and the Y direction (lateral direction). Only the F_x drives the boat move forward. It contributes to the thrust. The lateral forces of the two propulsors counteract each other. For each propulsor, the thrust generated is:

$$F_{1x} = F_{2x} = \sum_{i=1}^{N} \frac{1}{2} C_l \rho A_i \left(\vec{v}_i \cdot \vec{v}_i\right) \cdot \sin\theta_i \tag{2}$$

where, C_l is the lift coefficient of the vertebras; A_i is the flapping area of the vertebra i; $\vec{v}_i$ is the flapping velocity relative to water flow of vertebra i; θ_i is the flapping angle of vertebra i; N is the vertebra number.

When the flapping amplitude of the propulsor is Θ, and the flapping frequency is f, for vertebra i the flapping velocity relative to water flow at position q is:

$$\vec{v}_i(q) = \left(u_i(q) \cdot \sin\theta_i - U\right) + \left(u_i(q) \cdot \cos\theta_i\right)\vec{i} \tag{3}$$

$$u_i(q) = \left(\sum_{j=1}^{i-1} l_j \cdot \omega_j + q \cdot \omega_i\right) \tag{4}$$

The tail is evenly constrained by the elastic caudal fin plate. Hence, during the flapping motion, it is assumed that the joint rotations are identical. As a result,

$$\theta_i = \frac{i}{N} \cdot \Theta \tag{5}$$

$$\omega_i = \frac{i}{N} \cdot 4\Theta \cdot f \tag{6}$$

Both the thrust and drag force relate to the cruising speed. When the thrust balances the drag force, the boat velocity is steady. The cruising speed can be obtained by solving the following equation.

$$\left(\sum_{i=1}^{N} C_l A_i \sin\theta_i - C_d S\right)U^2 - \left(\sum_{i=1}^{N} 2C_l A_i u_i(q)\sin^2\theta_i\right)U + \sum_{i=1}^{N} C_l A_i u_i^2(q)\sin\theta_i = 0 \tag{7}$$

This is a quadratic function. There exist two solutions. For the double hull boat, the speed increases from zero to cruising speed and then cruises steadily. Hence, the smaller positive solution should be chosen.

IV. Motion Control Scheme

The motion of the boat is controlled by the flapping of the propulsors. The motion control is similar to that of the robotic fish, but with a lot of differences. The following presents the cruising control scheme and turning control scheme.

A. Cruising Control

The flapping propulsor of the boat is borrowed from the robotic fish. One straightforward cursing method is letting the two propulsors flap as that of a robotic fish, as shown in Fig. 5 (a). The robotic fish flaps its tail side to side to gain thrust. During the swimming, a lateral force is unavoidable. As a result, the fish body sways when it moves forward. In cruising mode 1, the lateral force is doubled as there are two propulsors. This is undesired for a boat, especially for ferry boat.

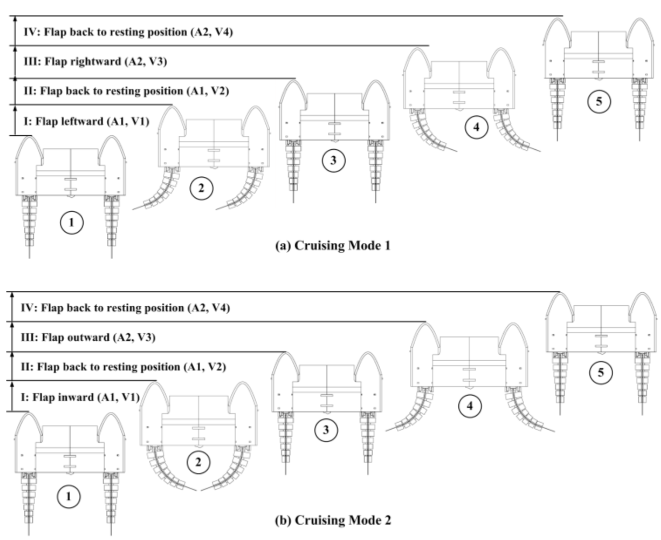

Fig. 5 Cruising Mode: Mode 1 –the two propulsors flap in the same way; Mode 2 - the two propulsors flap in an opposite manner

Another cruising method is letting the two propulsors flap in an opposite manner, as shown in Fig. 5 (b). In this mode, the lateral forces produced by the two propulsors counteract with each other. Hence, the boat forward motion is more stable. Without considering the coupling effect, the thrust generated in the two cruising modes are the same. However, in cruising mode 2, a water jet is generated when the two propulsors flap inward, this will yield additional thrust.

For both cruising modes, a full flapping cycle has four steps. In mode 1, these are: I – flap leftward; II – flap back to the resting position; III – flap rightward; IV – flap back to the resting position. In mode 2, the four steps are: I – flap inward; II – flap back to the resting position; III – flap outward; IV – flap back to the resting position. The flapping amplitudes and velocities in the four steps can be the same or independent.

B. *Turning Control*

Turning is important for a boat maneuvering in the harbor. For the wire-driven double hull boat there are several ways to turn around. Fig. 6 shows three modes for turning leftward. The brown block represents for the hulls, and the two curves represent for the two propulsors. The modes for turning rightward are similar.

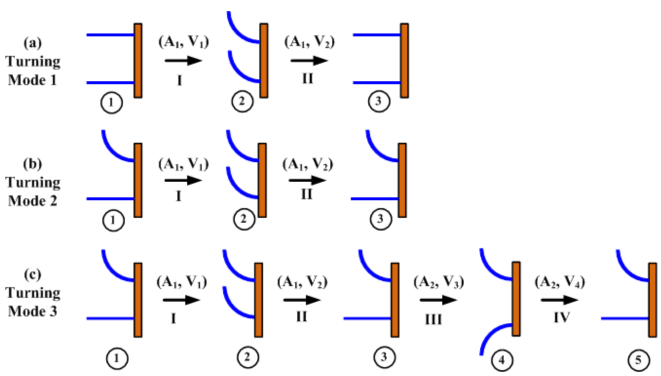

Fig. 6 Turning Control: Three Turning Modes

In turning mode 1, the two propulsors flap in the same way. At first, they flap leftward, and then flap back to the resting position. This is the same as the turning method used in the wire-driven robotic fishes [14-16]. In turning mode 2, the left propulsor flaps leftward to the limit, acting as a rudder. The right propulsor at first flaps leftward and then flaps back to the resting position. In these two modes, one full flapping cycle has two steps. In turning mode 3, the left propulsor still acts as a rudder. The right propulsor flaps as in the cruising mode 1. There are four steps in the flapping cycle. Similar to that in the cruising mode, the flapping amplitudes and flapping velocities in the four flapping steps can be the same or independent.

V. Prototype and Experiment Validation

A prototype was built as shown in Fig. 7. The width of the boat is 320 mm and the length is 348 mm. The total mass of the boat is 1055 gram. The spacing distance between the two propulsors is 240 mm, which guarantees that even if the two propulsors bends 90° they don’t collide with each other. The hull structure and vertebras of the propulsor are fabricated using 3D printing. The material used is ABS plastic. A plastic fin plate is fixed to the vertebra, which not only defines the profile of the propulsor but more importantly confines the joint rotations. Each propulsor is driven by a servo motor (TowerPro MG995). A commercial micro controller (AVR atMega 16) is used to control the two servo motors. The servo motors are controlled in the same way as in [13-16]. A set of 4 AA batteries is used as the power supply.

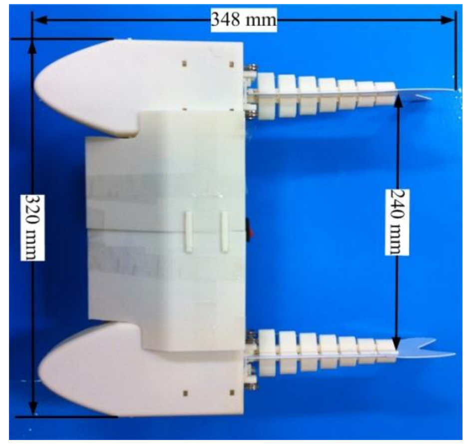

Fig. 7 Double-Hull Boat Prototype

Swimming tests are carried out in a water tank. The length of the tank is 1.8 m, and the width is 0.9 m.

A. *Cruising Performance*

Cruising performance of the boat is tested in still water. The boat is placed in the water tank and the propulsors are controlled to flap with different flapping amplitudes and flapping frequencies. In the test, the boat travels through a fixed distance as shown in Fig. 8. By gauging the time needed to pass by, the cruising speed of the boat is calculated.

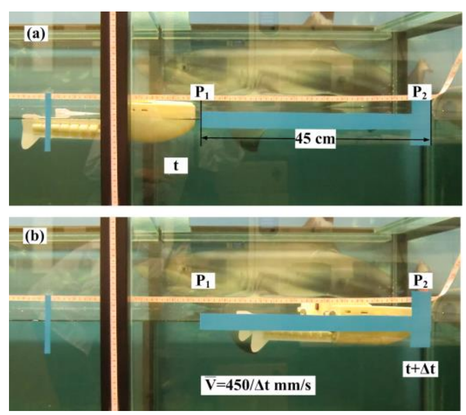

Fig. 8 Cruising Speed Measurement

As predicted, in cruising mode 1, the boat sways side to side during the cruising. Therefore, in the test, only cruising mode 2 is studied in detail. The flapping amplitude of the propulsors increases from 10 degrees to 90 degrees. The flapping velocities in the four steps are constant. In the first set of test, the flapping frequency is 0.25 Hz. In the second set of test, the flapping frequency is 0.5 Hz.

Fig. 9 shows the results. The circles show the measured cruising speed in the first set of test. It is seen that with the increasing of flapping amplitude, the cruising speed increases continuously from 5.1 mm/s to 58.6 mm/s. However, the increasing rate is not constant. The rate is larger when the flapping amplitude is less than 40 degrees. The blue curve shows the simulated cruising speed from the propulsion model. The simulation agrees well with the experiments. They have a similar trend, and the values are close. However, the measured speed is larger than the simulation constantly. The reason is manifold, including discrepancy in drag and lift coefficients, motion error, etc. In the simulation, the drag coefficient is 0.5, and the lift coefficient is 1.0. Also, in this cruising mode, a water jet is generated when the propulsors flap inward. This will yield an additional thrust, but is not considered in the propulsion model.

When the flapping frequency is 0.5 Hz, with the increasing of flapping amplitudes, the cruising speed has a similar increasing trend. The cruising speed almost doubled as shown by the red squares. Such as when the flapping amplitude is 30°, the speeds are 17.2 mm/s and 44.8 mm/s respectively, the ratio is 2.6; when the flapping amplitude is 90°, the speeds are 58.6 mm/s and 99.7 mm/s respectively, the ratio is 1.7. For all the flapping amplitudes, the averaged ratio is 2.12. From the simulation, this ratio is 2.0. Or, the cruising speed is linearly related to the flapping frequency. Also, the measured speed is constantly larger than the simulated results. The reason is similar. It is noted that, when the flapping amplitude is close to 90°, the speed increase rate fluctuates significantly. One reason is the size of the tank is limited; a significant wave appears in the test. This affects the boat cruising a lot.

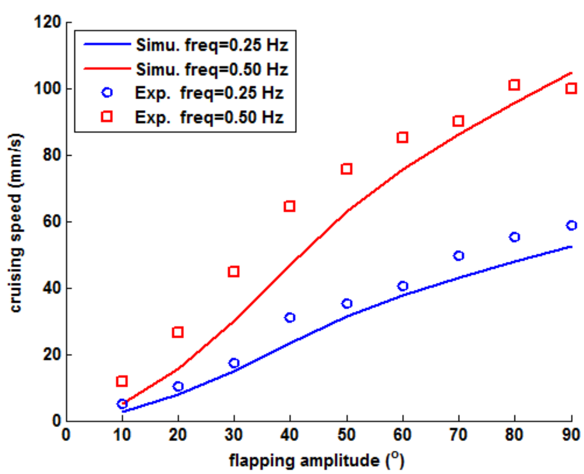

Fig. 9 Cruising Performance of the Wire-Driven Double Hull Boat

For both sets of tests, the cruising speed shows a similar trend with the increasing of flapping amplitude. Fig. 10 shows the increase rate. In the figure, the curves represent for the speed increment when the flapping amplitude is increased by 1°. From the figure, at small flapping amplitude, with 1° increase of amplitude, the cruising speed increase rate is positive correlated to the flapping amplitude. The inflection point is 40°. Beyond this amplitude, the speed increment reduces. Especially at large flapping amplitude, the increment becomes steady. Therefore, from the energy saving point of view, the optimal flapping amplitude is 40°. In practice, the flapping amplitude can be in the range of 40° and 60°.

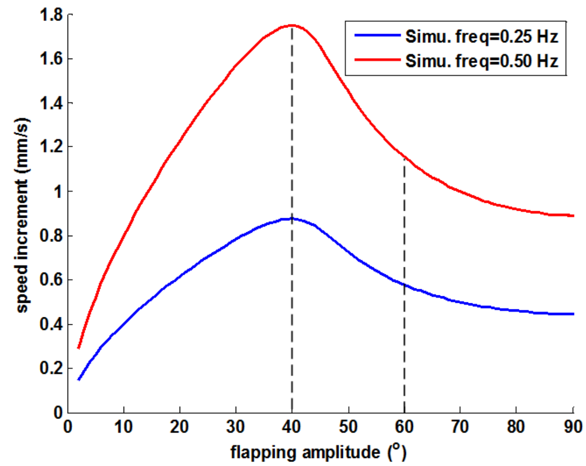

Fig. 10 Cruising Speed Increase Rate w.r.t. Flapping Amplitude

In the previous test, the flapping velocity is constant during the four steps. In the following test, the flapping velocities in step II and step IV are two times of the velocities in step I and step III. The flapping period is kept constant. This is named the fast and slow mode. The cruising speed is measured as previously. The results are summarized in Fig. 11. From the figure, by using the fast and slow scheme, the cruising speed of the boat is increased. When the flapping frequency is 0.25 Hz, the average speed ratio of the two motion schemes is 1.345. When the flapping frequency is 0.5 Hz, the average speed ratio is 1.093. In the experiment, when the propulsor flapping frequency is beyond 0.5 Hz, the water flow becomes turbulent, the flow bounce back from the walls and affects the boat cruising performance a lot. This is one reason why the speed ratio at higher flapping frequency is lower.

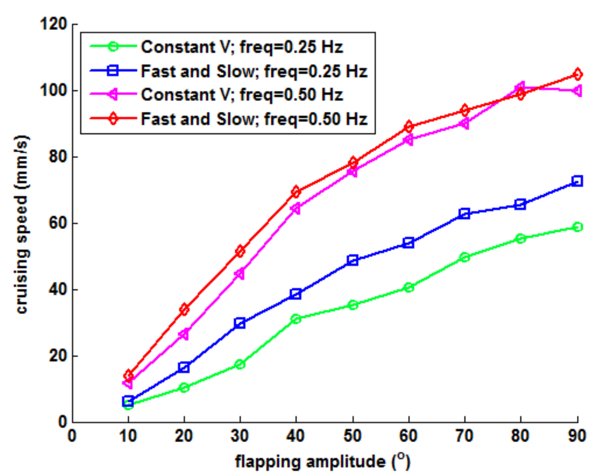

Fig. 11 Cruising Performance Comparison of Two Motion Modes

B. *Turning Performance*

In the tests, three turning modes are tested. The boat is placed in still water and is then controlled to turn leftward. The width of the boat is 320 mm; the minimum space needed for flapping is 480 mm. However, the width of the tank is only 900 mm. Hence, in the turning test, the boat cannot turn a full circle. The turning trajectory is recorded through the video frames, and the turning radius and turning speed is estimated from the trajectory. The turning radius used here is the turning radius of the boat center, or the averaged turning radius of the two hulls.

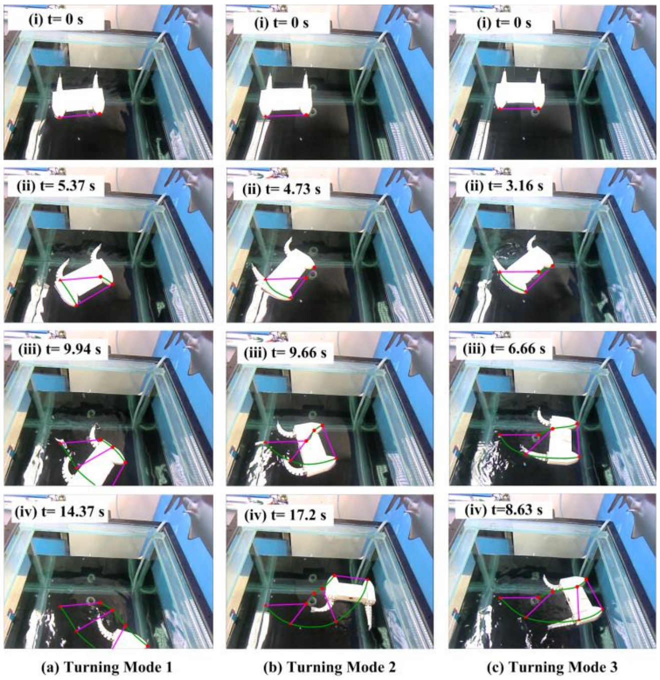

Fig. 12 Turning Performances of the Boat in the Three Turning Modes

In the first turning mode, the two propulsors flap together, the flapping frequency is 0.5 Hz, and the flapping amplitudes are both 90°. In the flapping cycle, the velocities in the two steps are the same. The turning trajectory is as shown in Fig. 12 (a). From the trajectory, the turning radius is about 800 mm (2.30 BL), and turning speed is 4.2 °/s. In the second turning mode, the left propulsor bends to the leftmost position, serving as a rudder. The right propulsor flaps as in Fig. 6 (b). The flapping amplitude is 90°, and the flapping frequency is 0.5 Hz. The flapping velocities in the two steps are the same. The turning trajectory is as shown in Fig. 12 (b). The turning radius is about 180 mm (0.517 BL), and the turning speed is 10.5 °/s. In the third turning mode, similarly, the left propulsor bends to the leftmost position. The right propulsor flaps as in Fig. 6 (c). The flapping amplitude is 90°, and the flapping frequency is 0.5 Hz. The flapping velocities in the four steps are the same. The turning trajectory is as shown in Fig. 12 (c). The turning radius is about 300 mm (0.862 BL) and the turning speed is 13.9 °/s.

From the results, turning mode 2 has the minimum turning radius, while turning mode 3 has the largest turning speed. When the two propulsors flap together, the performance is inferior to using one propulsor as a rudder.

VI. Conclusion

This paper presents a novel double-hull boat with two wire-driven flapping propulsors. Each propulsor contains seven joints, while is driven by one motor. The underactuated design greatly simplifies the structure and control. The joints rotations are confined by a uniform plastic caudal fin plate. During the flapping, all the joints rotations are nearly the same. A reactive propulsion model is developed for the double hull boat. Two cruising methods and three turning modes are introduced, which give guidance to the operation of flapping propelled double-hull boat. Experiment results show that, the double hull design improves the boat stability a lot. When the flapping frequency is low, the model predicts the cruising performance well. From the model, the optimal flapping amplitude is 40 degree. In the test, the maximum cruising speed is 0.323 BL/s, the minimum turning radius is 0.517 BL, and the maximum turning speed is 13.9°/s.

References

[1] *Shipping and World Trade*. Available: http://www.marisec.org/shippingfacts/keyfacts/
[2] M. S. Triantafyllou and G. S. Triantafyllou, "An efficient swimming machine," *Scientific american,* vol. 272, pp. 64-71, 1995.
[3] H. Hu, "Biologically Inspired Design of Autonomous Robotic Fish at Essex," *Proceedings of the IEEE SMC UK-RI Chapter Conference 2006 on Advancs in Cybernetic Systems,* pp. 1-8, September 2006.
[4] *BUAA Robotic Fish*. Available: http://news.buaa.edu.cn/dispnews.php?type=5&nid=1920&s_table=news_txt
[5] J. Z. Yu, M. Tan, S. Wang, and E. Chen, "Development of a biomimetic robotic fish and its control algorithm," *Ieee Transactions on Systems Man and Cybernetics Part B-Cybernetics,* vol. 34, pp. 1798-1810, Aug 2004.
[6] *Tai-robot-kun*. Available: http://www.youtube.com/watch?v=WINc1mV-L8Y
[7] *Firo Robotic Fish*. Available: http://www.youtube.com/watch?v=OpTRaKBD6PY
[8] O. Laser, "Fin propulsion boat," ed: Google Patents, 1982.
[9] *Proteus*. Available: http://www.rbbi.com/folders/tech/product/penguin.htm#proteus1
[10] *Double hull boat*. Available: https://en.wikipedia.org/wiki/Catamaran
[11] Z. Li and R. Du, "Design and analysis of a biomimetic wire-driven flapping propeller," in *Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS & EMBS International Conference on*, 2012, pp. 276-281.
[12] Z. Li and R. Du, "Design and Analysis of a Bio-Inspired Wire-Driven Multi-Section Flexible Robot," *Int J Adv Robotic Sy,* vol. 10, 2013.
[13] Z. Li, R. Du, M. C. Lei, and S. M. Yuan, "Design and Analysis of a Biomimetic Wire-Driven Robot Arm," in *Proceedings of the ASME 2011 International Mechanical Engineering Congress & Exposition*, 2011, pp. 11-17.
[14] Z. Li, R. Du, Y. Zhang, and H. Li, "Robot Fish with Novel Wire-Driven Continuum Flapping Propulsor," *Applied Mechanics and Materials,* vol. 300, pp. 510-514, 2013.
[15] Z. Li, W. Gao, R. Du, and B. Liao, "Design and Analysis of a Wrie-Driven Robot Tadpole," in *International Mechanical Engineering Congress & Exposition (IMECE 2012)*, Houston, Texas, USA, 2012.
[16] B. Liao, Z. Li, and R. Du, "Robot Tadpole with a Novel Biomimetic Wire-driven Propulsor," presented at the IEEE International Conference on Robotics and Biomimetics (ROBIO 2012), Guang Zhou, China, 2012.
[17] Z. Li, R. Du, and Y. Yao, "Flying Octopus - A LTAV with Wire-Driven Flapping Wings," in *International Mechanical Engineering Congress & Exposition (IMECE 2012)*, Houston, Texas, USA, 2012.
[18] Z. Li and R. Du, "Design and implementation of a biomimetic wire-driven underactuated serpentine manipulator," *Transaction on Control and Mechanical Systems,* vol. 1, 2012.
[19] Lighthil.Mj, "Large-Amplitude Elongated-Body Theory Of Fish Locomotion," *Proceedings Of the Royal Society B-Biological Sciences,* vol. 179, pp. 125-+, 1971.