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Design of a New Propulsion Mechanism of Imitating Duck's Webbed-feet

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Abstract

With the wide application of the underwater vehicle in ocean exploration, bionics propulsion aroused intensive interest among researchers. Bionic locomotion of aquatic animals has the advantages of highly maneuver, power-efficient endurance and so on. In the paper the mechanism of duck's swimming is studied and a novel bionics propulsion mechanism is designed and analyzed. The mechanics of underwater vehicle is investigated by ADAMS. Dynamics response of the system is analyzed by using numerical method. The simulation results suggest that the designed propulsion mechanism can imitate the movement modes of the duck's webbed feet, and implement the motion of vehicle in fluid environment.

***Keywords**: underwater vehicle, bionics, propulsion, ADAMS*

1. Introduction

Underwater vehicle is widely used in surveying the marine environment, exploring marine resources and so on. The traditional propulsion mode of underwater vehicle is propeller impetus. Reza Llka, Asghar Gholamian [1] presented a new method for optimum design of a five-phase surface-mounted PMSM for propeller impetus to achieve minimum loss and magnet volume with an increased torque. They also untilized finite element analysis to validate the accuracy of the design. Yushi Wei, Mingyu Fu et al. [2] bulit a quadratic programming thrust allocation and management system to solve the complex thrust allocation problems of dynamic positioning ship with azimuth thrusters. The validity and excellent performance of this method was proved by the simulation.

The aquatic animals locomotion has been found that it has the advantages of high efficiency, low noise and high mobility [3]. Chris Watts, Euan McGookin [4] took the salmon as research object to establish an underwater vehicle imitation fish propulsion system, and have established its mathematical model and performed the dynamic analysis and the thrust contrast with propeller propulsion system. P.Krishnamurthy, F.Khorrami et al. [5] took the electric rays as research objects to design a six degree of freedom rigid body model BAUV (Biomimetic Autonomous Underwater Vehicles), and have performed its motion simulation and physical experiment, which provided a flexible, extensible platform for the study of fish class athletic stance and the design of imitation fish vehicle. Jun Gao [6] took the cownose ray as mock object and have proposed a model of imitation fish based on the pectoral fin flapping propulsion, and have carried out the experimental research. The results showed that this institution could improve the speed of pectoral fin flapping-wing robotic fish. Dan Xia [7] proposed a dynamic model of wavy swimming of fish-like robot, and took the thunniform bio-inspired mode as research object, proposed a kind of numerical method for solving the problem that the bionic prototype autonomous swimming, and had done the optimization of tail fin based on this method.

In addition, other organisms in nature, such as sea turtles, ducks and squid, their ways of swimming have become increasingly proficient through natural selection and self-evolution [8]. Although sea turtles, ducks have larger body, they have strong explosive power, maneuverability and stability. Baowei Song, Hao Ding et al. [9] gave an introduction of the concepts, characteristics and application of flapping-wing UUV, and discussed some of the key technologies of flapping-wing propulsion. Mingjun Zhang [10], Dinghui Chu [11] et al have

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conducted some research on the propulsion technology of bio-hydrofoil, and have done the performance test of the biomimetic hydrofoil propulsion system. It provided a basis for control strategy of biomimetic hydrofoil propulsion system. Zhenlong Wang, Guanrong Hang et al. [12] have performed the intensive study of jet swimming mechanism of squid, and explored its application in biomimetic underwater vehicle. Gal Ribak, John G. Swallow et al. [13] have carried out the detailed observation and research on duck's movement when it was foraging underwater, and analyzed the specific law of flipper's motion when duck resisted buoyancy and ensured the attitude stability underwater.

Based on the bionics principle and the analysis of the duck's swimming style and the structure of its webbed feet, a new kind of propulsion mechanism of imitation duck's webbed feet was designed in this paper, it could imitate duck's motion style and provide driving force for the body. The force situation of biomimetic propulsion mechanism in water was analyzed by using Morison Equation. The mechanical system dynamics software ADAMS was used to simulate and analyze the whole system. It has broad application prospects in the field of the bionic propulsion of underwater vehicle.

2. Biomimetic Propulsion of Duck

2.1. Analysis of the Motion Style of Duck's Webbed Feet

Ducks could move in the water through pulling forward by using their webbed feet. After the actual observation of duck's movement underwater, we found that the flippers movement could be divided into two phases: stroking back and contracting forward. When the flippers stroke back in the water, the webbed feet fully open to increase the contact area with water and drive the body by the reacting force from water. When the flippers contract forward, the webbed feet fully close to decrease the contact area with water. Figure 1 shows the movement of duck's webbed feet in the water.

(a)

(b)

Figure 1. Movement of Duck's Webbed Feet

2.2. Structure of Bionic Propulsion

Structure of underwater vehicle with biomimetic propulsion mechanism is shown in Figure 2. It includes the body, steering engines and propulsion mechanisms.

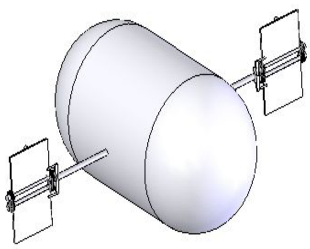


Figure 2. The Total Structure Figure

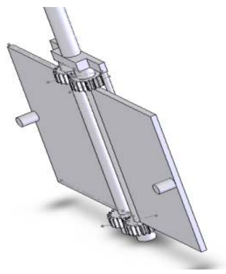
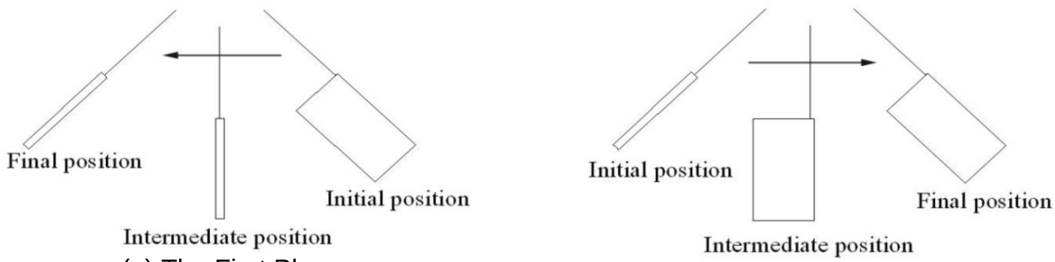


Figure 3. The Specific Structure

The specific structure of biomimetic propulsion mechanism based on duck's feet is shown in Figure 3. It is composed of a swaying shaft, a pair of swinging fins, a pair of meshing gears (fixed with the swinging fins), limit bars and buffer blocks.

When the swaying shaft strokes back in the water, the swinging fins would fully open by the action of water to increase the contact area with water, limit bars would limit the fins' position to get a maximum area. It would gain the maximum reacting force to drive the body. When the swaying shaft contracts forward, the swinging fins would fully close by the action of water to decrease the contact area, the resistance would also be decreased. Buffer blocks are used to decreasing the instantaneous contact force of the swaying shafts.

The working process of the biomimetic propulsion mechanism could also be divided into two phases. The first phase is to stroke back which is shown in Figure 4(a). The swinging fins are closed in the initial position. With the shaft's swinging, it would gradually open by the action of water. When the shaft reaches the intermediate position, the swinging fins fully open and it would gain a maximum area with water, the reacting force would drive the body and the shaft keeps on swinging to the final position. The second phase is to contract forward which is shown in Figure 4(b). The shaft starts swinging from the initial position (the final position in the first phase). The swinging fins would gradually close by the reaction of water. When the shaft gets to the intermediate position, the fins would fully close and the contact area with water would be minimum. The shaft keeps on swinging to the final position (the initial position in the first phase).



(a) The First Phase (b) The Second Phase

Figure 4. The Working Process of Biomimetic Propulsion

3. Force Analysis of Biomimetic Propulsion Mechanism

This paper supposes the motion rules of the shaft is:

$$\phi = S_0 \sin(2\pi \frac{t}{t_0}) \tag{1}$$

$$\dot{\phi} = \frac{2\pi}{t_0} S_0 \cos(2\pi \frac{t}{t_0}) \tag{2}$$

$$\ddot{\phi} = -\left(\frac{2\pi}{t_0}\right)^2 S_0 \sin(2\pi \frac{t}{t_0}) \tag{3}$$

Where:

φ : swaying angle

$\dot{\varphi}$: angular velocity

$\ddot{\varphi}$: angular acceleration

t : swaying time

t_0 : swaying cycle

S_0 : swaying amplitude

This paper suppose that the swaying amplitude was 60°, the swaying cycle was 2s. We suppose that the underwater vehicle is in the hydrostatic environment, which meant that the buoyancy is equal to gravity.

$$mg - F_b = 0 \tag{4}$$

Where:

m : total mass of underwater vehicle system

F_b : total buoyancy of underwater vehicle system

The total force on the underwater vehicle system includes drag force and inertia force. We deal with the total force based on the Morison equation.

$$F_d = -(C_M \, \rho V \, \vec{a}_\perp + \frac{1}{2} C_D \, \rho \, A v_\perp \left| v_\perp \right|) \tag{5}$$

Where:

C_M : inertia coefficient

C_D : resistance coefficient

ρ : fluid density

D : body's diameter、swinging fin's width

V : volume of the body and the swinging fin

A : projected area of body and fin perpendicular to the velocity

$\vec{v}_\perp$: velocity normal to the fin surface

$\vec{a}_\perp$: acceleration normal to the fin surface

4. Movement Simulation and Analysis

The mechanical system dynamics software ADAMS is used to simulate and analyze the biomimetic propulsion in this paper. Firstly the simplified 3-D model was built in the 3-D mapping software Solidworks. And then the model is imported into ADAMS.

We defined the materials of all the parts, added all sorts of hinged institutions and the driving equation based on Equation (1) (Figure 5), the hydraulic resistance and the hydrodynamic force based on Equation (5). Neglecting all the friction among all the parts, we supposed the simulating time was 30s. The results are shown in Figure 6.

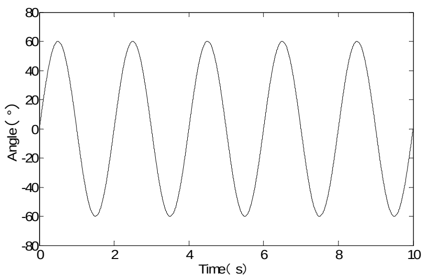
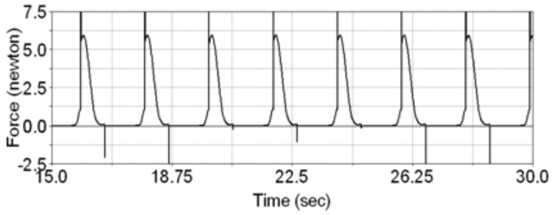
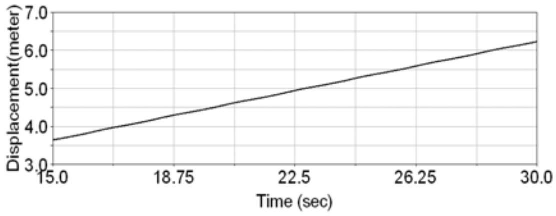


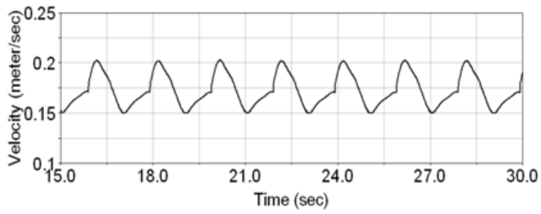
Figure 5. The Motion Rule of the Shaft ($t_0 = 2s$)



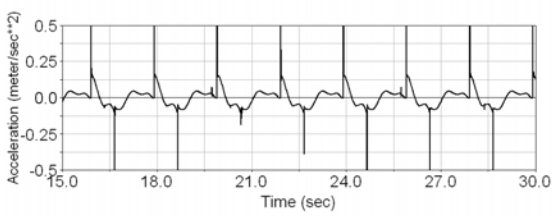
(a) Hydrodynamic Force on the Swinging Fins



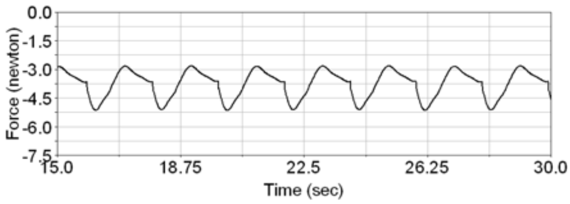
(b) Displacement of Underwater Vehicle



(c) Velocity of Underwater Vehicle



(d) Acceleration of Underwater Vehicle



(e) Hydraulic Resistance of Underwater Vehicle

Figure 6. ADAMS Simulation Results ($t_0 = 2s$)

The simulation results in Figure 6 show that this propulsion mechanism of imitation duck's webbed feet could accurately simulate the motion process of duck's webbed feet in water and the motion of the total system is similar to the duck's motion in water. Figure 6 shows the displacement, velocity and acceleration of underwater vehicle and the stress state of the body and swinging fins at different moment. There appeared instantaneous increase and decrease of hydrodynamic force on the swinging fins and hydraulic resistance of underwater vehicle. The reason is that the swinging fins crashed the limit bars and buffer blocks when it fully opened and closed. It would disturb the motion of the total system.

Further considering the impact of various factors on the law of motion, this paper decided to change the motion rules of the shaft. We supposed the swaying cycle was 1s (Figure 7). The simulation results are shown in Figure 8.

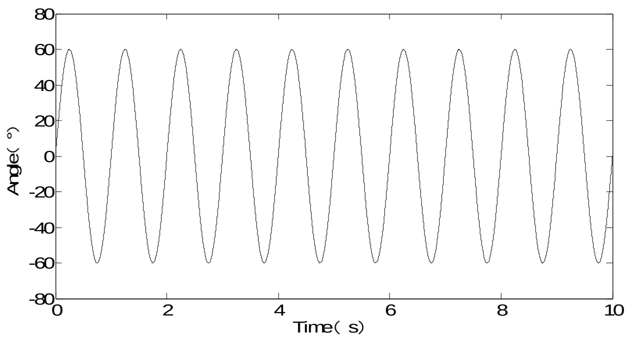
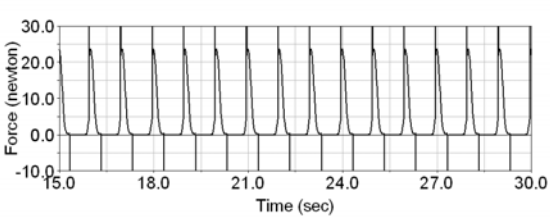
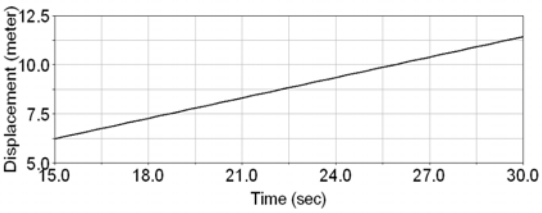


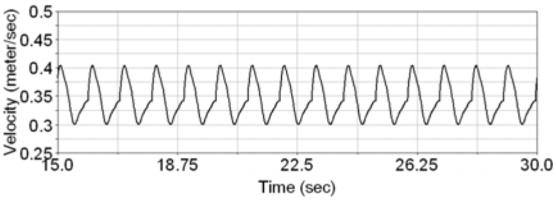
Figure 7. The Motion Rule of the Shaft ($t_0 = 1s$)



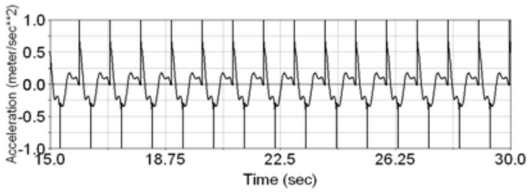
(a) Hydrodynamic Force on the Swinging Fins



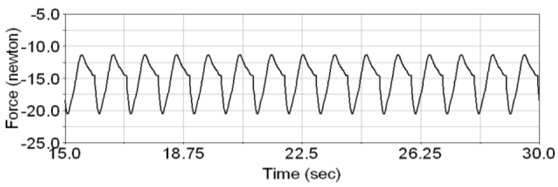
(b) Displacement of Underwater Vehicle



(c) Velocity of Underwater Vehicle



(d) Acceleration of Underwater Vehicle



(e) Hydraulic Resistance of Underwater Vehicle

Figure 8. ADAMS Simulation Results ($t_0 = 1s$)

In contrast to Figure 6, the results in Figure 8 show that to increase the swaying frequency of shaft, the average hydrodynamic force on the swinging fins and the average velocity and acceleration of underwater vehicle would increase. And the average hydraulic resistance of underwater vehicle would also increase. However the displacement diagram in Figure 8(b) shows that the increase of velocity is obvious. It means that this biomimetic propulsion could provide different kinds of driving force for underwater vehicle to satisfy the need of different environments.

5. Conclusion

In this paper, a new propulsion mechanism was designed and analyzed. This paper firstly analyzed duck's swimming style and the structure of its webbed feet. A new kind of propulsion mechanism of imitation duck's webbed feet was designed based on the bionics principle and the analysis above. The physical structure of the propulsion mechanism was specially designed. The force situation of biomimetic propulsion mechanism in water was analyzed by using Morison Equation. The mechanical system dynamics software ADAMS was used to simulate and analyze the whole system. The results suggest that the designed propulsion mechanism can imitate the movement modes of the duck's webbed feet to provide driving force for underwater vehicle.

Acknowledgements

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