Research and Development of Robotic Fish Based on Elastic Oscillation Fin System

*Ikuo Yamamoto*\(^1\) and Tomokazu Hiratsuka\(^2\)

\(^1\), \(^2\) Department of Mechanical Systems Engineering, The University of Kitakyushu, 1-1 Hibikino, Wakamatsu, Kitakyushu, Fukuoka 808-0135, Japan

\(^1\) yamamoto@kitakyu-u.ac.jp

ABSTRACT

The authors research and develop a flapping wing type robotic fish (shark ray robot) with flexible tail fin as an advanced underwater vehicle. The flapping wing consists of multi-joints mechanism to get lift force and rotation moment for high maneuvering characteristics of motion. The tail fin is designed by elastic oscillating system and developed to produce strong propulsion force for higher speed maneuvering. In addition, a trim balance mechanism is designed to get the trim of pitch motion. The developed the shark ray robot has higher maneuverability by strong lift force of flapping wing and propulsion force of tail fin. Also, the shark ray robot can cruise quietly and avoid twining by seaweeds, and is effective for environmental parameter sensing and acquisition. The shark ray robot was designed by elastic oscillating fin system and the model with tail fin and main wings has been constructed. Then, its effectiveness has been successfully confirmed by numerical simulation and tank test. In addition, the authors proposed an effective fin drive due to resonance, and had positive outcomes.

1. INTRODUCTION

Creatures have evolved in their own way over many generations to adapt to the natural environment (Hertel 1963, Morris 1998). By clarifying their maneuvering mechanism scientifically and applying the resulting knowledge to engineering, it is possible to create a new product and technology (Nachtigall 1998, 2000, Yamamoto 2001). In particular, the author has been among the first in the world to develop a control system of oscillating fin propulsion (Yamamoto 1993). Then, many studies...
about the control system of the oscillating fin were reported by other research groups (Anderson 1998, Gopalkrishnan 1994).

The development of underwater robot has been actively pursued in recent years. A bio-maneuvering type underwater vehicle has been developed through new and different approaches, namely the observation of marine creatures such as fish and the engineering application of their maneuvering mechanism. This robot is widely known as a “robotic fish.” The first developed robotic fish, a sea bream, has gained a reputation in the world for swimming just like the real thing without power and communication cable, being admired for its high level of technology in various magazines (Madeen 2004). The technology has been employed to build various kinds of robotic fish such as a coelacanth, carp, and whale (Yamamoto 2008). This paper describes the beginning, history, and future of the development of the robotic fish and the underwater vehicle with fin propulsion system, which have been created as part of research on bio-maneuvering type underwater vehicle.

2. THE BEGINNING OF DEVELOPMENT

In the 1980s when studying a variety of marine vehicle robots, the author began to seek an alternative propulsion actuator to propellers. It was the beginning of this research. In the process of research, assuming that the movement of a fish fin might be a possible key, the author often visited aquariums between actual works or on holidays to observe the motion of fish. It was found, with continuing observations, that the swimming motion of fish varied with living environment and that their body structure and propulsion method had evolved uniquely so as to suit the swimming motion. The author’s interest shifted to the creation of robotic fish itself. Meanwhile, the need for a scientific approach was realized. Therefore the development of robotic fish was promoted through scientific approach based on technologies of fluid mechanics, material engineering, vibrational science, tribology, electrical engineering, and controlling engineering (Yamamoto 1999).

3. DEVELOPMENT OF FLEXIBLE OSCILLATING FIN PROPULSION SYSTEM

The development of the robotic fish started with the development of an actuator that could realize fishlike fin movement. Through the observation of the motion of fish, it has been found that fish swim efficiently using flexibility of pliable fins, giving the actuator the name of flexible oscillating fin propulsion system.

Fig. 1 shows the drive principle of early flexible oscillating fin propulsion system. The flexure like a fish fin was produced by variously changing elastic modules of the flexible oscillating fin. The optimal shape of the fin was also chosen through numerical simulation and tank test. Then, the maneuverability was tested with a small craft, on which the oscillating fin propulsion system was installed. Here, it was found that the oscillating fin propulsion system enabled the craft to move back and forth as well as turn right and left using a fin. Neural network algorism, which application was not common in the field other than mathematical theory at that time (in 1990), was also installed on the control computer, establishing a system to learn a way of movement (Yamamoto 1994).
4. DEVELOPMENT OF ROBOTIC FISH

4.1. Development of Robotic Sea Bream

While underwater radio transmission, sonar information technology, high-reality fairing technology, and image recognition technology were developed, based on the development of flexible oscillating fin propulsion system, a robotic sea bream was developed as shown in Fig. 2, 3, and 4. It weighs 2.6 kg and is 60 cm long. It has an internal battery and makes 3-dimensional movement without cables. Its speed is 30m/min. The surface is made of silicone resin. It cruises autonomously or by remote control via a computer. Fig. 5 shows the swimming test of this robot (Yamamoto 2003), and Fig. 6 shows the flow test of this robot.
Fig. 3. Internal structure of robotic sea bream.

Fig. 4. System configuration of robotic sea.

Fig. 5. Robotic fish swimming in the water.
4.2. Fully-automatic swimming system

A fully-automatic swimming system was developed for the purpose of having a robotic fish swim automatically in amusement facilities. In this system as shown in Fig. 7, the robotic fish is located by the ultrasonic sensor on the tank and automatically controlled via computer. The control instruction is sent to the fish by underwater signal. This system enabled a series of automatic swimming; the robotic fish starts swimming automatically when the control button is pressed, automatically corrects its depth and course, swims to a recharger when the battery runs low, and starts swimming again after automatic charging. Fig. 8 shows the robotic fish swimming in the water. As the robotic fish has a CPU, central processing unit, it is also possible to give the fish itself a self-controlled feature (Yamamoto 2003).
5. FLAPPING WING TYPE ROBOTIC FISH

The authors have been developing many prototypes of AUV (Autonomous Underwater Vehicle), and were studied flapping wing type which could be used to collect oceanographic data and water samples. Its outline seems like manta birostris (manta ray) as shown in Fig. 9. The developed one joint system of flapping wing was proved strong lift force in width of 24cm wings through experimental analysis. Fig. 10 shows its photo. This system is using only one actuator and one joint to make propulsion force. When actuator rotates, length of upper and lower plate of elastic oscillating fin that consists flapping wing begin to differ. Therefore, the wing flaps as shown in Fig. 11. These flexible plastic plates exist as their support, and thin rubber film exist to make propulsion force. Flapping wing thus can realize its flexible movement. This one joint system shows about 0.38N of propulsion force in the tank experimental, and authors estimate its lift force about 20N. The multiple joints propulsion system has twisting mechanism to realize higher maneuverability of underwater vehicle. Fig. 12 shows its photo. In the twisted mode as shown in Fig. 13, maximum rotating torque is varying from about 1.7N\(\cdot\)m to -1.6N\(\cdot\)m, so this system can be use to change propulsion directions and attitude. This multiple flapping wing propulsion system will enable underwater vehicles to have strong maneuverability. The developed system has much possibility for propulsion and maneuvering system of AUV.
Fig. 10. Flapping wing with one joint system.

Fig. 11. Structure of flapping wing.

Fig. 12. Flapping wing with multiple joints system (flat mode).

Fig. 13. Flapping wing with multiple joints system (twisted mode).
6. MECHANISM OF TAIL FIN WITH SLIDING BELT

Tail fin mechanism based on elastic oscillating theory, which can produce strong propulsion force has developed as shown in Fig. 14. It has drive belt sliding mechanism as shown in Fig. 15. This mechanism uses one center support plate and then two sliding belt besides. Actuator pushes tow sliding belt to drive tail fin. It also has balance weight to balance trim of robotic fish as shown in Fig. 16. It enables robotic fish to keep horizontal attitude and to control trim. These mechanisms produce higher maneuverability of this robotic fish.

Fig. 14. Tail fin of robotic fish.

Fig. 15. Drive belt sliding mechanism of tail fin of robotic fish.
7. NEW UNDERWATER VEHICLE BASED ON SHARK RAY

The new underwater vehicle has wing and new tail fin structure for strong propulsion force higher maneuvering characteristic of turning round, etc. This new biomimetic underwater vehicle is developed based on study of shark ray (Rhina ancylostoma). Fig. 17 shows shark ray. The shark ray has unique structure. Its shape of head and wing like shark, and its shape of tail like ray. They can be stabilizer, propulsion and rudder, in each as shown in Fig. 18. Authors are planning to combine these functions in one robotic fish to realize high maneuverability. Fig. 19 shows an external view of prototype underwater vehicle with a single plate fin mechanism used on performance evaluation tests. No.1 & 2 motors provide thrust force, and No.3 & 4 motors keep balance of vehicle as main fins. In this performance evaluation test, we used only No.1 & 2 motors.
The authors measured thrust force for thrust performance evaluation of the prototype underwater vehicle. Fig. 19 shows the experiment system for the propulsion force measurement. This experiment system is a new measuring method. The system is able to measure propulsion force without fixing the underwater vehicle. Fig. 20 shows the experiment system for the propulsion force measurement. Specifically, first, a position of the center of gravity of the vehicle is fitted with wire-rope in water tunnel. Second, the wire-rope is divided into two directions, and is retracted backward. Finally, the thrust force is measured by a force gauge. Fig. 21 shows the external view of experiment system. The experiment showed that 1Hz of frequency of fin provided up to 60N of propulsion force. Therefore, it is considered that if the frequency increases, a greater propulsion force is provided. As a result, the experiment showed that the structure of the prototype underwater vehicle was effective.
8. COLLABORATIVE CONTROL OF TAIL FIN AND WINGS

The elastic oscillating tail fin and flapping main wings are concertedly controlled. As a result, the underwater vehicle swims in mimicry of the shark ray. Fig. 23 shows an example of collaborative control of the tail fin. The tail fin is able to swing between narrow and wide by collaborative control. Fig. 24 shows a block diagram of controller of servomotors. The each servomotor is connected in a daisy chain, and is controlled by instructions from a microcomputer.
9. RESONANCE FIN DRIVE MECHANISM

A normal fin drive oscillates by motor. Meanwhile a resonance fin drive found to be particularly useful for effective fin drive (Fig. 25.).

\[ f_n = \frac{\omega_n}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{k}{M}} \quad (1) \]

Where, \( f_n, \omega_n, k, \) and \( M \) are a natural frequency, natural angular frequency, constant of spring and mass, respectively. \( k, M \) is determined by a quality of material. Therefore \( f_n \) is calculated by Eq. (1). In fact, if the fin is driven by the calculated natural frequency, the fin effectively drive. The authors calculated of the natural frequency through experiment with a model robot (Fig. 26.), and experimented the resonance fin drive.
The calculation flow of the natural frequency is following:

1) Irradiate the fin of model robot with a laser.
2) Flick one’s fingers at the fin in order to oscillate.
3) Measure oscillation of fin from motion of laser.

Fig. 27, 28 and 29 shows the measuring result of each fin. The natural frequency of each fin is calculated by an oscillatory waveform shown in Fig. 27, 28 and 29. Then the fins are oscillated by the natural frequency. At present, the authors perform further experiments toward the practical use of the resonance fin drive.
Fig. 27. A measuring result of natural frequency of left wing.

Fig. 28. A measuring result of natural frequency of right wing.

Fig. 29. A measuring result of natural frequency of tail fin.
CONCLUSION

The authors designed and developed the flapping wing type underwater vehicle with flexible tail fin as the new underwater vehicle in mimicry of the shark ray. The flapping wings consist of multi-joints mechanism to get lift force and rotation moment for high maneuvering characteristics of motion. The tail fin is designed by elastic oscillating theory and developed to produce strong propulsion force for high speed maneuvering. The flapping wings and the tail fin are concertedly controlled by the daisy-chained controller. As a result, the new underwater vehicle is able to reproduce various moves, and is able to swim like the shark ray. In addition, the authors proposed an effective fin drive due to resonance, and had positive outcomes.

ACKNOWLEDGMENTS

Authors would like to thank the Knowledge Cluster Initiative of MEXT (Ministry of Education, Culture, Sports, Science and Technology) for a grant that made it possible to execute a part of the study.

REFERENCES