STUDY ON TURNING PERFORMANCE OF A FISH ROBOT

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Abstract:

Underwater robots are widely used in the fields of ocean development, ocean investigation and marine environmental protection. Autonomous underwater robots are planed, and several robots have been already developed. They need higher efficiency of propulsive performance and good dynamics performance. On the other hand, it is well known that several kinds of fish have a good ability of turning and acceleration. If the underwater robot that can simulate a fishlike locomotion is developed, it is considered that the robot has dynamics performance similar to fish.

The aim of this study is to develop a fish mimetic underwater robot with good dynamics performance. At first, we discussed turning modes for the fish robot that uses tail swing. Based on the discussion, the prototype fish robot, which has 340 mm body length, was developed. Just after manufacturing, swimming speed at straight propulsion was measured. Next, we measured turning performance with the suggested turning modes. As the result, it was confirmed that frequency, amplitude and leaning of the tail affect the turning performance. Still more, we made sure that the prototype fish robot turned quickly from straight propulsion and stationary state.

INTRODUCTION

Underwater robots are widely used in the fields of ocean development, ocean investigation and marine environmental protection [1]. As the request that the underwater operation should be carried out more efficiently becomes strong, autonomous underwater robots are planed, and several robots have been already developed. They need higher efficient of propulsive performance and good dynamics performance.

On the other hand, a fishlike swimming mechanism is expected as a new propulsive device for underwater robots, because it has a possibility to get high-speed swimming and efficient propulsion [2]. In order to develop an intelligent underwater robot with a high performance, a study on fish robot has been started since 1999 at Ship Research Institute. We also have taken much interest in good dynamics performance of fish. It is considered that the fish robot strongly contributes to the underwater operation, if the robot gets good dynamics performance similar to fish.

In this paper, we discuss turning modes for the fish robot that uses only tail swing. Based on the discussion, a small prototype fish robot is developed. And fundamental performance of the prototype fish robot is measured.

TURNING MODES

Though real fish turn skillfully using not only tail fin but also pectoral fins or ventral fins, we determined a structure of the prototype fish robot, which turns with only swing of tail fin. As the tail fin is utilized both propulsion and turning, the fish robot gets simple structure and easy control for swimming. In the case of turning with only swing of tail fin, we think that there are three turning modes

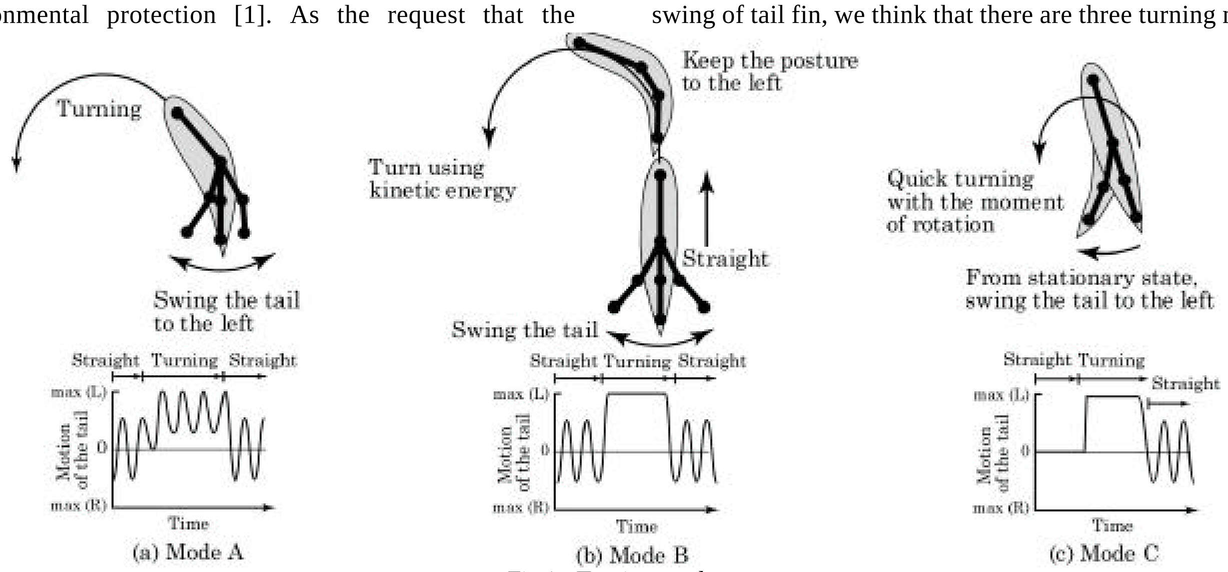


Fig.1 Turning modes

shown as follows (Fig. 1).

Mode A

Fig. 1 (a) shows the case of Mode A. The fish robot swings its tail only to one side during a turning. We consider that this mode is the most fundamental and important turning mode, because the robot can turn with various turning diameter and speed in this mode.

In this turning mode, a head and a body of the fish robot are equivalent to a rudder, and the tail peduncle and the tail fin are equivalent to a screw propeller of the ship. If we attend to the resemblance of these functions, we can analyze this mode and control the robot easily.

Mode B

Fig. 1 (b) shows the case of Mode B. At first, the fish robot swims straight, and gets kinetic energy. Next, the fish robot turns its tail to one side, and keeps the posture to the side. Then the fish robot turns by hydrodynamics force. It is considered that this mode gets smaller turning diameter than that of Mode A.

In Mode B, as the stationary posture of the fish robot with the leaning of the tail is regarded as a wing, its friction force and lift force can be estimated. It is possible to analyze the turning performance and control the movement by considering the kinetic energy at the straight propulsion.

Mode C

Fig. 1 (c) shows the case of Mode C. The fish robot swings its tail to one side rapidly from stationary state. In this turning mode, inertia force and friction force of the moving tail and a body are changed to the moment of rotation. This mode has excellent characteristics. It is possible to turn from the stationary state, and its turning diameter is the smallest in the whole modes. However, it is difficult to control turning speed and turning angle. Also, in order to get quick turning, it is necessary that the power source for tail swing should have sufficiently high torque.

Though there are the other turning modes combined the above three modes, only these basic turning modes are treated in this paper.

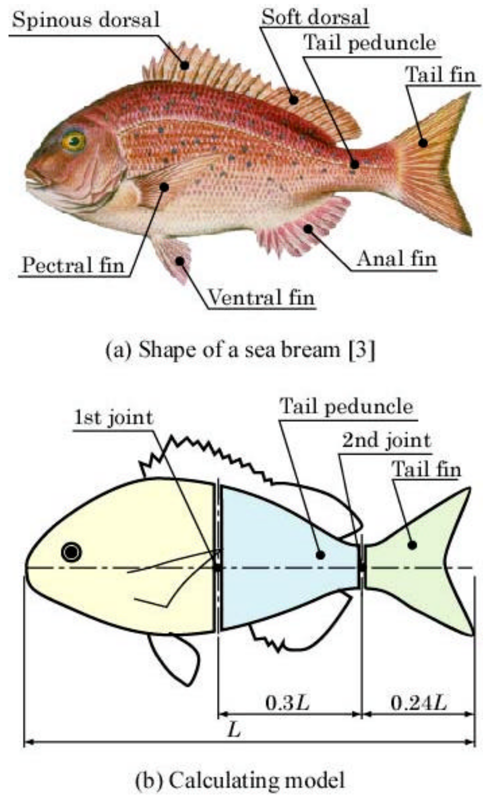
DEVELOPMENT OF A PROTOTYPE FISH ROBOT

Basic Design

After discussion of the above turning modes, it is considered that the fish robot with a thin body, that has taller body height compared with body width, is suitable for quick turning and changing of swimming speed. Thus, a prototype fish robot is designed with referring to a shape of sea breams as shown in Fig. 2 (a).

For acquiring smooth motion like fish, it is better to have as many joints as possible. However, from the limitation of structure, the prototype fish robot has only two joints at a tail peduncle and a tail fin. Two servomotors for a radio control model (R/C) drive the each joint.

In order to determine a type of the servomotors and size of the prototype fish robot, the maximum torque of the servomotor is calculated by a simple method. The method



(a) Shape of a sea bream [3]

(b) Calculating model

Fig. 2 A sea bream and calculation model

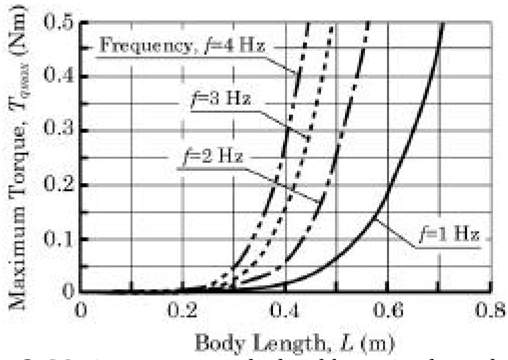


Fig. 3 Maximum torque calculated by a simple method

focuses only maximum speed of tail swing, without consideration of hydrodynamics around the fish robot. Size of the tail and locations of joints are determined as shown in Fig. 2 (b). When the tail peduncle and the tail fin are regarded as each plane, the maximum torque of the servomotor is calculated easily. Figure 3 shows an example of calculated results. Based on this calculation, we adopt the servomotor that has the maximum torque of 3.0 kgf·cm (=0.29 N·m), and determine body length of the prototype fish robot.

Control System and Moving Pattern

The servomotors are controlled by a personal computer with a R/C transmitter and a D/A converter. A control program on the personal computer realizes various motion patterns.

Figure 4 shows outline of the fundamental motion pattern. It is used at the following experiments of straight propulsion and turning performance of Mode A. Amplitude of tail peduncle from the central axis of body, A_1 (degree) and amplitude of tail fin from the central axis of the tail peduncle, A_2 (degree) are obtained by following equations.

$$A_1 = K_a A_{1\max} \sin 2pft + A_{1\max}(1 - K_a)K_i \qquad (1)$$

$$A_2 = K_a A_{2\max} \sin(2pft - b) + A_{2\max}(1 - K_a)K_i \qquad (2)$$

Here, f is frequency (Hz) of swing, t is time (sec), and b is phase angle between the tail peduncle and the tail fin. $A_{1\max}$ and $A_{2\max}$ are maximum amplitudes of the tail peduncle and the tail fin, respectively. They are determined mainly by limit angles of the link mechanism The angle is $A_{1\max}$=30 degrees, and $A_{2\max}$=40 degrees. K_a is amplitude factor (set to 0~1). K_i is leaning factor (set to -1~1, set to 0 at straight propulsion).

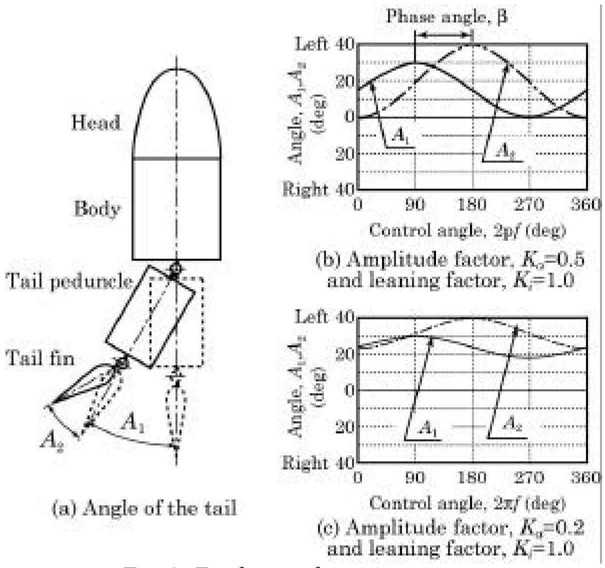


Fig. 4 Fundamental moving pattern

Mechanism

Arrangement of the servomotors, a battery and a R/C receiver is determined based on detail discussions; i. e., a simple structure, a link mechanism, location of seal devices, a thin body, and the maximum amplitude of a tail fin. Figure 5 shows the schematic view of the prototype fish robot, and Fig. 6 shows its photograph. The principle particulars are listed in Table 1. Body length is about 340 mm. The R/C receiver is set in a head. The battery is set in below side of a body to lower the center of gravity. One servomotor that drives a tail peduncle is set in the body part. Another servomotor that drives a tail fin is set in the tail peduncle.

Rods of a link mechanism are waterproofed using rubber boots for R/C models. Locations of joints and size of the tail are determined based on the shape of sea breams. However, a few joints and size of mechanical parts limit the location and the size.

The head and the upper side of body are molded using hard urethane foam. In the operation, a wood float is set at upper side of the body (see Fig. 6). Thus, the prototype fish robot swims a constant depth. In order to adjust balance of gravitation and buoyancy, steel weights are located in the

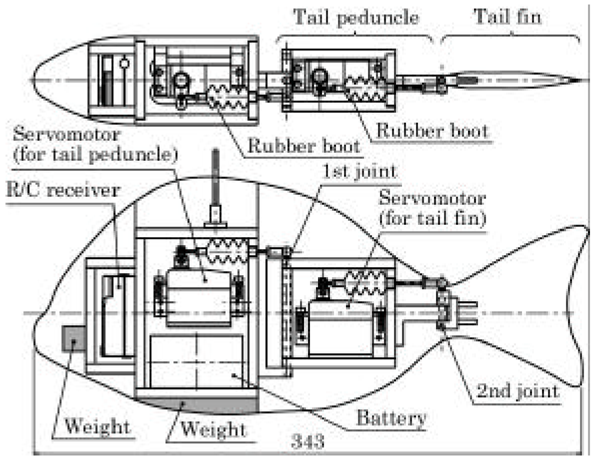


Fig. 5 Schematic view of the prototype fish robot

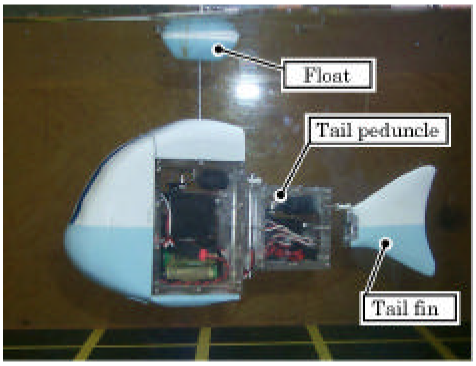


Fig. 6 Photograph of the prototype fish robot

Table 1. Principle Particulars of the prototype fish robot

Body length	340 mm
Weight	1.1 kg
Number of joints	2
Servomotor	Futaba, S148
Number	2
Maximum torque	0.29 N·m (3.0 kgf·cm)
Maximum speed	0.22 sec / 60 degrees
Battery	6.0 V

head and lower side of the body.

It is necessary that the tail peduncle should be molded using very soft material to move the tail flexibly. As it is difficult to select the material, we give up the idea of molding the tail in the following experiments.

It is well known that soft material is suitable for a tail fin [4]. However, in order to keep a setting motion strictly, the tail fin of the prototype fish robot is made of hard wood.

PERFORMANCE OF THE PROTOTYPE FISH ROBOT

Swimming Speed at Straight Propulsion

Before investigating the turning performance of the prototype fish robot, straight speed is measured with changing of frequency: f, phase angle: b, and amplitude factor: K_a. In this case, leaning factor: K_i, is set at 0.

Figure 7 shows the experimental result of the relationship between amplitude factor: K_a, frequency: f, and swimming speed: V. In this figure, swimming speed: V increases with increasing of frequency: f. In the case of higher range of frequency, increasing rate of swimming speed decreases. The swimming speed: V increases with increasing of amplitude factor: K_a. When amplitude factor: K_a increases, increasing rate of swimming speed decreases. It can be thought that the shape of the prototype fish robot is not suitable for high-speed swimming in the focus of hydrodynamics. It is considered that motion of the servomotors may not realize the programmed motion. The servomotors can not follow sufficiently high speed in high frequency areas or high amplitude areas.

Figure 8 shows the experimental result of the relationship between amplitude factor: K_a, phase angle: b, and swimming speed: V. This figure shows that the optimal phase angle at which maximum swimming speed is 20~50 degrees. Amplitude of the rear end of tail fin increases with decreasing of phase angle: b. Thus, it is considered that smaller phase angle obtains strong propulsive force in the prototype fish robot. This result does not agree with the well-known fact in wing theory that the phase angle of 90 degrees obtains the maximum propulsive efficiency.

In the above experiments, the maximum swimming speed is about 0.2 m/s at K_a=0.6, f=2.3 Hz, and b=20 degrees. The prototype fish robot swims 0.6 times of its body length per second. This is not sufficiently high speed, because several kinds of real fishes keep swimming about 2 times of its body length per second [2]. It is caused that the maximum frequency is limited by the performance of servomotors. As the drag of the prototype fish robot is larger than real fish, a body shape and a surface of tail peduncle should be reformed to get high speed.

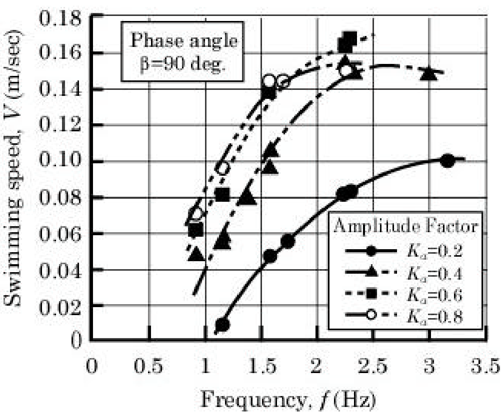


Fig. 7 Swimming speed as a function of frequency

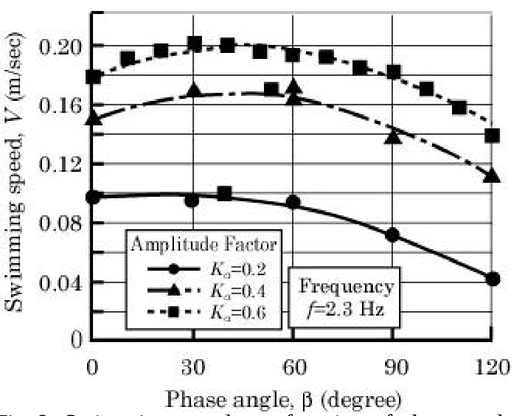


Fig. 8 Swimming speed as a function of phase angle

Turning Performance

Turning performance is measured at a small water tank, which is 0.9 m length, 0.9 m width and 0.4 m depth. A video camera is located on upper side of the water tank. Turning diameter: D, turning time per one revolution (360 degrees): T, and others are derived from pictures taken by the video camera.

(a) Mode A

To realize the movement of fish robot in Mode A, we make a composite photograph (Fig. 9). In the photograph, it is confirmed that the prototype fish robot has a correct circular orbit.

Figure 10 shows the experimental result of the relationship between amplitude factor: K_a, turning diameter: D, and turning time: T at frequency: f = 2.3 Hz, and phase angle: b = 90 degrees. This figure shows that D decreases with decreasing of K_a, and T increases with decreasing of K_a. It is caused that the rate of leaning increases relatively with decreasing of K_a, though propulsive force decreases with decreasing of K_a. Also, D decreases with increasing of K_l,. T is not strongly affected K_l.

Figure 11 shows the experimental result of the relationship between amplitude factor: K_a, and swimming speed: V (=$2\pi D/T$), at the same condition of Fig. 10. In the figure, white dots represent that of straight propulsion: K_l=0, from Fig. 7. In the figure, V increases with increasing of

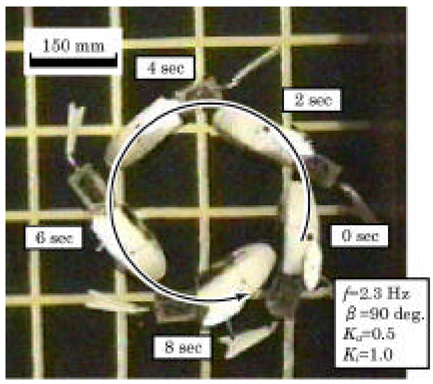


Fig. 9 Composite photograph of Mode A

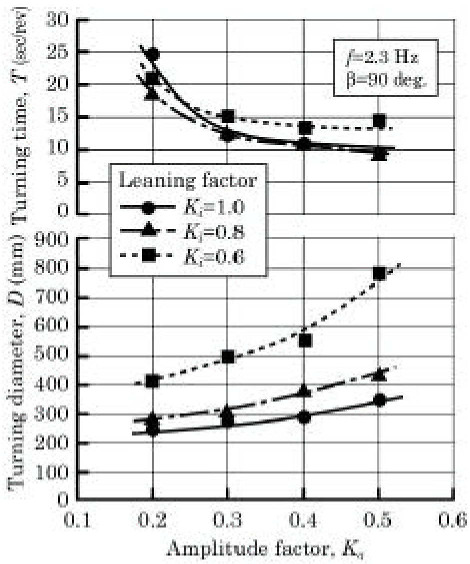


Fig. 10 Effects of amplitude and leaning

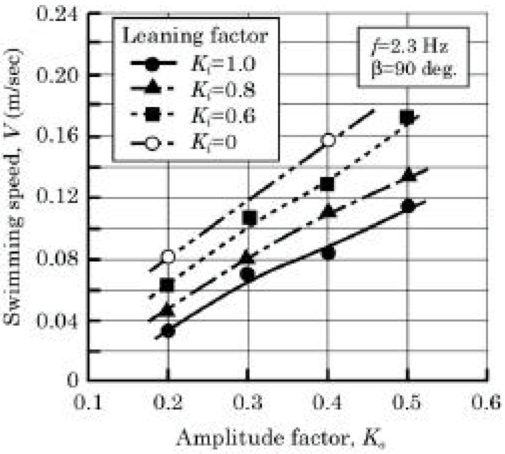


Fig. 11 Swimming speed as a function of amplitude and leaning

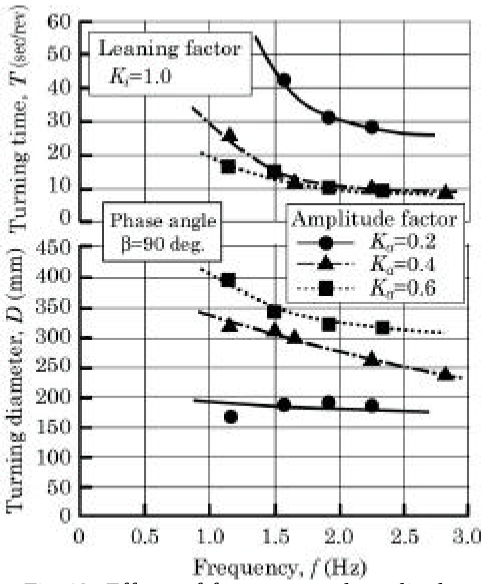


Fig. 12 Effects of frequency and amplitude

K_a, and V decreases with increasing of K_i. It is caused that increasing of K_i, obtains decreasing of propulsive force.

Figure 12 shows the experimental result of the relationship between frequency: f, turning diameter: D, and turning time: T, at leaning factor K_i = 1.0, and phase angle *b* =90 degrees. In the figure, D and T decrease with increasing of f. In order to get good turning performance, it is necessary that the fish robot should have high-speed tail swing.

From the above experiments, the effects of turning performance by frequency: f, amplitude factor: K_a, and leaning factor: K_i, are clarified. It is considered that the fish robot is controlled with good dynamics performance, when the each characteristic is well managed.

(b) Mode B

Figure 13 shows photographs at the experiment of Mode B. In this experiment, the prototype fish robot swims straight with initial speed of 0.15 m/s (see Fig. 13 (a)). It stops the tail swing, and straightens itself at one time. Next, the fish robot turns its tail to the left side in a short time, about 0.3 second (see Fig. 13 (b)~(c)). Then, the fish robot turns the left with the stationary posture (see Fig. 13 (d)~(f)).

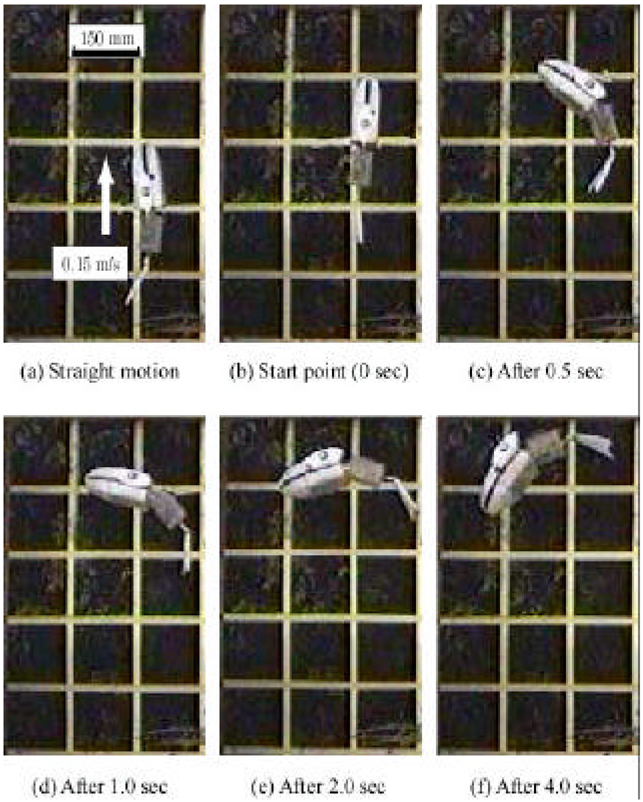


Fig. 13 Photographs of Mode B

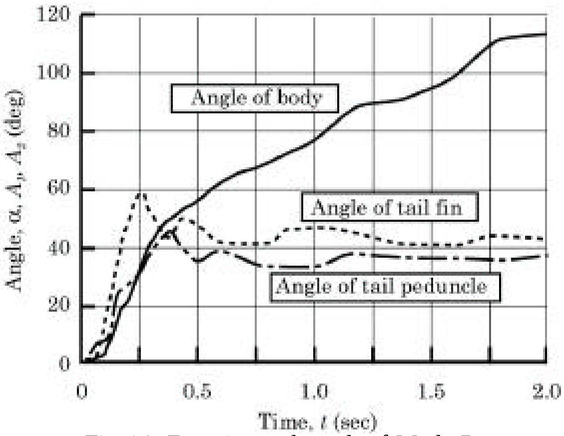


Fig. 14 Experimental result of Mode B

Figure 14 shows the relationship between time: t, angles of joints: A_1, A_2, and turning angle of the body: *a*. The body turns quickly with moving of the tail at first 0.3 second, and *a* reaches to about 40 degrees. And then, the body turns slowly with stationary posture. This turning mode has smaller turning diameter than that of Mode A. When the fish robot is given higher initial speed, it can get good turning performance similar to fish. Because hydrodynamics force caused by the leaning tail, like lift force of wing, the performance is affected strongly with increasing of initial speed.

(c) Mode C

Figure 15 shows a composite photograph of Mode C shown in Fig. 1 (c). In this experiment, the prototype fish robot keeps its tail to the right as the first stationary state.

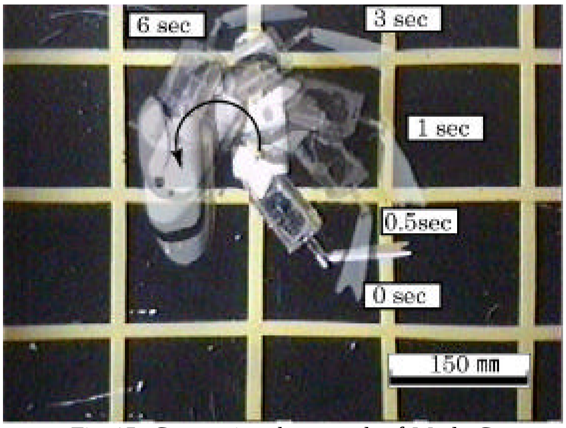


Fig. 15 Composite photograph of Mode C

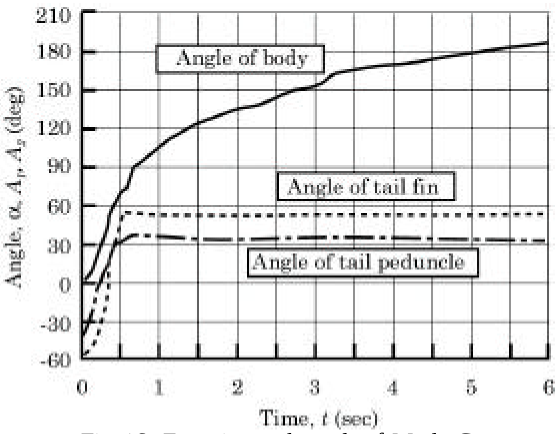


Fig. 16 Experimental result of Mode C

Next, the fish robot swings the tail to the left in a short time, about 0.5 second. This turning mode has very smaller turning diameter than that of other modes.

Figure 16 shows the relationship between time: t, angles of joints: A_1, A_2, and turning angle of the body: a. In the figure, a reaches to about 100 degrees after 0.7 second.

It is considered that this mode has high possibility as the turning mode for a practical used by underwater robot, because this mode realizes to turn from the stationary state. It is difficult to get the same performance using a previous system consist of a screw propeller and a rudder. However, in the case of Mode C, it is difficult to control the turning angle accurately, and its power source for the tail swing should have sufficiently high.

DISCUSSION

In this paper, we discussed the turning modes of the fish robot, and a prototype fish robot was developed. From the experiments for turning performance, it was confirmed that the prototype fish robot realized to turn in various modes with the tail swing. The experimental results are summarized as following.

(1) In the case of Mode A, turning diameter decreases with decreasing of amplitude of the tail fin, and with increasing of leaning. Also, turning diameter decreases with increasing of frequency, though the effect of frequency is not so strong.

(2) In the case of Mode A, turning time per one revolution (360 degrees) decreases with increasing of frequency and amplitude. The effect of leaning is not strong.

(3) Tuning diameter of Mode B is smaller than that of Mode A.

(4) The prototype fish robot turns quickly by Mode C from the stationary state.

From the experiments, we have found some problems and subjects for getting higher turning performance under existing circumstance. They were clarified as follows.

(1) The servomotors do not have sufficiently performance. They can not move high speed in high frequency areas or high amplitude areas.

(2) It is necessary to develop a high quality control system for motion of the servomotors. We think that the fuzzy theory is effective for the control of turning performance.

(3) As the body shape and a surface of tail peduncle are not suitable for high-speed swimming, the drag is large.

(4) The prototype fish robot has large rolling motion, when it swims low speed. It is considered that the balance of gravitation and buoyancy at the moving tail affects propulsive and dynamics performance.

(5) In this paper, three turning modes are classified. In the next step, their combined modes must be discussed.

(6) We have not developed the prediction method for turning performance yet. It is necessary to analyze the turning performance in detail. The analysis derives turning diameter and turning angle for various types of body shapes and power source.

CONCLUSION

In this study, the prototype fish robot was developed, and its fundamental performance was clarified. We think that the results contribute a development of a new and high performance propulsive device for underwater robots. When a high performance fish robot that can swim skillfully and intellectually is developed, it will be used for the fields of ocean development, ocean investigation and marine environmental protection.

Many experimental studies are needed as the next step. We can be convinced that the fish robot has a possibility of getting good dynamics performance similar to fish by the experimental studies.

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