A New Type of Fish-Like Underwater Microrobot

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***Abstract*—This paper presents a new prototype model of an underwater fish-like micro robot utilizing ionic conducting polymer film (ICPF) actuator as the servo actuator to realize swimming motion with three degrees of freedom. Biomimetic fish-like micro robot using ICPF actuator as a propulsion tail fin and a buoyancy adjuster for a micro robot swimming structure in water or aqueous medium is developed. The overall size of the underwater micro robot prototype shaped as a fish is 45 mm in length, 10 mm in width, and 4 mm in thickness. It has two tails with a fin driven respectively, a body posture adjuster, and a buoyancy adjuster. The moving characteristic of the underwater micro robot is measured by changing the frequency of input voltage from 0.1–5 Hz in water and the amplitude input voltage from 0.5–10 V. The experimental results indicate that changing the amplitude and the frequency of input voltage can control the swimming speed of proposed underwater microrobot.**

***Index Terms*—Actuator, underwater micro robot.**

I. Introduction

INTRACAVITY intervention is expected to become increasingly popular in the medical practice, both for diagnosis and for surgery. As we know, many kinds of micro actuator such as an electrostatic actuator, a piezoelectric actuator, a giant magnetostrictive actuator (GMA), a shape memory alloy actuator, a polymer actuator and an optical actuator have been actively investigated for their potential applications to micro machine technologies. Recently many micro robots have been developed for various purposes due to the advances of the precise process technology, and further progress in this field is expected. One of the features that a micro robot has is a good possible advantage to work in a very small space. For instance, with medical technology a common application is to perform a delicate surgical operation supported by using micro machines thus avoiding unnecessary incisions. For an industrial application the use of micro robots is also proposed to maintain factory pipelines. As well as the medical case, the use of micro robots can help to avoid dismantling and reassembling. Micro robots can restrict their work to affected part or the breakdown spot and do not give unnecessary influence on their surroundings. Mother machine is the kind of robot that transports such micro robots and micro modules for accurate local work and operation in a very small space. In the medical field and in Industry application, a new type of fish-like micro robot that can swim smoothly in water or aqueous medium has urgently been demanded [1], [2] . The fish-like micro robot is one of the micro and miniature devices, which is installed with sensing and actuating elements. It can swim smoothly in water or aqueous medium such as use for in pipe inspection and microsurgery of blood vessel.

Oftentimes nature can be the best source of learning tool to devise mechanical equivalents for the process of locomotion. As we know direct conversion of chemical to mechanical energy has been pursued by many scientists to date in order to achieve high efficiencies. Among various forms of locomotion forward swimming motion of a fish in water has been the subject of interest by zoologists, marine biologists and engineers. The advantage of wavy motion of the swimming body as compared to mechanical propeller used in man-made swimming structures are numerous and can be attributed to its high efficiency of energy conversion noiseless propulsion and utilization of the energy of the surrounding medium. Mechanical swimming structures such as those that replicate undulating motion by means of linkages and other interfacing parts face the same problems as propellers with low efficiencies and excessive thermal energy generation. Recently, several types of fish-like micro robot using shape memory alloy (SMA) actuator, GMA actuator, piezoelectric (PZT) actuator, and polymer actuator have been reported so far [3]–[8]. However, there are some problems, such as compact structure, low response, leaking electric current, safety in water, and so on.

It is our purpose to develop a type of fish-like micro robot that can swim smoothly in water or aqueous medium. It has the characteristics of flexibility, driven by a low voltage, good response and safety in body. Biomimetic fish-like propulsion using an ionic conducting polymer film (ICPF) actuator as a propulsion tail fin for an underwater microrobot swimming structure in water or aqueous medium is developed. The ICPF actuator is made from the film of perfluorosulfonic acid polymer (Nafion 117, du Pont and company) chemically plated on both its ides with platinum. In many points, the ICPF actuator is superior to usual polymer gel actuator such as fast response, driven by low voltage (about 1.5 V) in wet conditions without electrolysis, safety in body, and so on [9]. It is now possible to replicate the undulating motion of marine animals using an ICPF actuator in a more direct way. This paper describes the new structure and motion mechanism of an underwater microrobot using an ICPF actuator, and discusses the swimming possibility of the microrobot in water. The experimental results indicate that changing the frequency and the amplitude of voltage can control the swimming speed and the buoyancy of the underwater micro robot.

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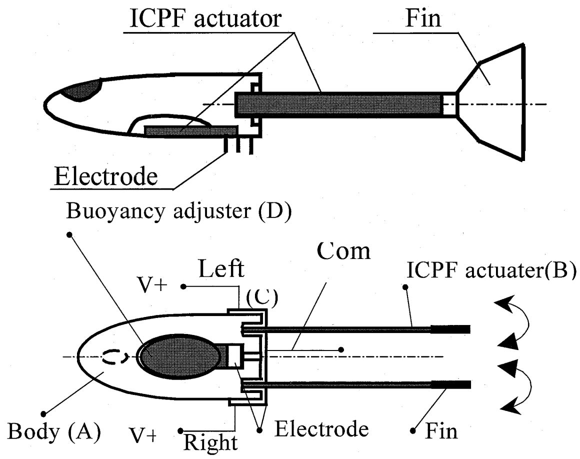


Fig. 1. (a) Structure of a tail. (b) Total structure of the micro robot.

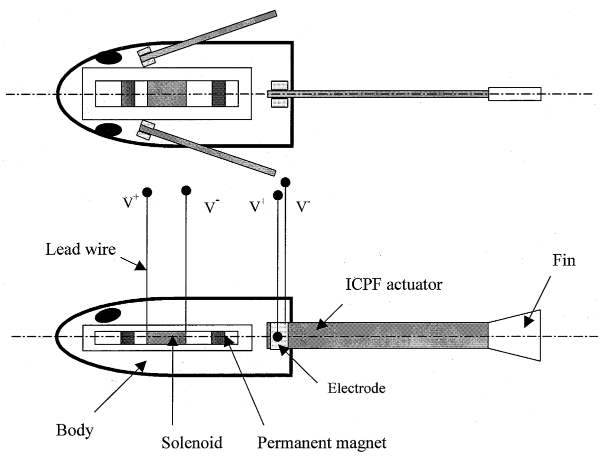
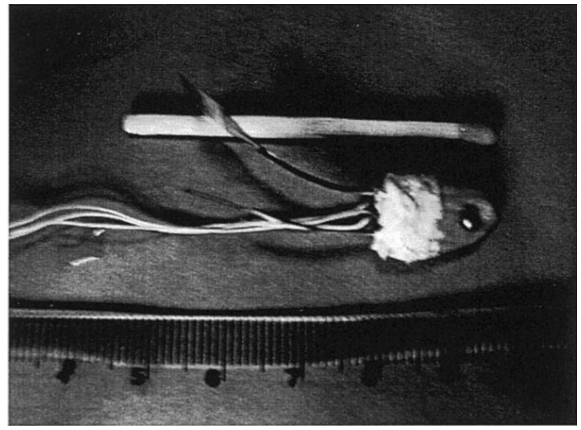
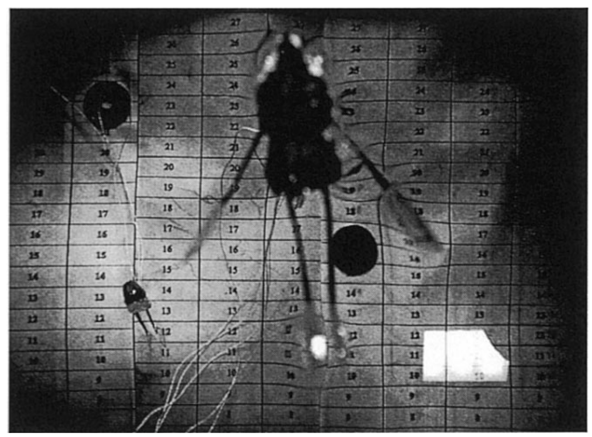


Fig. 2. Adjusting structure of the micro robot posture.



(a)



(b)

Fig. 3. (a) View of the developed micro robot 1. (b) View of the developed micro robot 2.

II. Structure of Micro Robot

A. Total Structure of the Micro Robot

Fig. 1 shows the basic structure of the developed underwater micro robot using an ICPF actuator.

This micro robot consists of the body made of wood material shaped as a fish (A), a pair of tail with a fin driven by the ICPF actuator, respectively, and (B), the lead wires for supplying electric energy to the ICPF actuators (C) and a pair of fins are installed in parallel structure for generating a large propulsive force. The fins are driven independently. The buoyancy adjuster under of the micro robot body is also driven by the same ICPF actuator. Fig. 2 shows the structure of the developed micro robot, which can adjust the body orientation by changing the center of gravity. The photo of the developed micro robot is shown in Fig. 3

B. ICPF Actuator

The ICPF actuator is made from the film of perfluorosulfonic acid polymer (Nafion 117, du Pont and Company) chemically plated on both its sides with platinum (one side is 0.003 mm in thickness). It is known as an ion exchange membrane. It is a kind of high polymer gel actuator, works only in water and in wet conditions. The ICPF is bent into anode side when about 1.5 V is applied to its surfaces. Displacement of the ICPF is proportional to the electrical voltage in put on its surface as the swelling of polymer gels. The ICPF actuator ($0.2 \times 3 \times 15$ mm) is cut in a strip to drive a fin for propulsion, and the ICPF actuator ($0.2 \times 4 \times 6$ mm) is used for buoyancy adjuster as shown in Fig. 1.

III. Motion Mechanism of Micro Robot

A. Theory of Fish Undulating Motion

According to the biomechanics theory, it is known that unlike carangiform mode of swimming where large undulating motion near or at the fish tail takes place anguilliform (eel-like) mode of swimming involves most of the fish body in undulation or wavy motion. Rosen [8] was among the first to explain kinematics of motion of a simple carangiform fish through his observations using simple hydrodynamic forces and phenomenon. He described that creation and evolution of vortices generated by the forward half of the body (head and after head of the fish) is the main reason for its propulsion through water. The fish further uses these vortices by the last 2/3 of its body (after half) to propel itself forward by thrusting its body against the seemingly fixed vortices and utilizing their rotational energy. This is called “vortex peg hypothesis.” The fish produces no net backward moving stream of water when swimming at constant

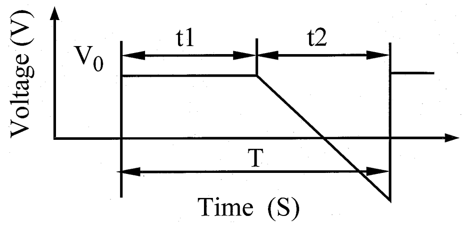


Fig. 4. Driving electric voltage.

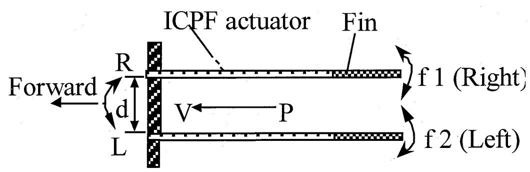


Fig. 5. Mechanism of micro robot using an ICPF actuator.

TABLE I
MOVING MOTION OF MICRO ROBOT

	Forward	Right Turn	Left Turn
Right ICPF Actuator frequency f1 / Left ICPF Actuator frequency f2	f1 = f2	f1 > f2	f1 < f2

speed. Only when the fish accelerates or turns around, a rearward current is created. The trail created by the fish is a system of large, slow spiraling vortices. They from a single row of vortices with direction of rotation reversing from one vortex to next. This row follows the path of the fish's head. The concave side of each flexural wave of the body of fish contains one vortex. All the main vortices are in line with and along the direction of travel of the fish. For a scaled fish, the mechanism of propulsion gets even more complex since the convex portion of the body in effect will have opened scales that act as small paddles on the side of the fish further pushing the vortices to propel the fish forward.

B. Motion Mechanism

The developed micro robot has two tails with a fin driven by the ICPF actuator, respectively, as shown in Fig. 1. A pair of fins is offset in the distance d, and driven by electric voltage of f1 and f2 frequency independently as shown in Fig. 4. A motion of a fin is described by combination of two kinds of motion, feathering and heaving. When proper phase difference appears between heaving and feathering, the fin generates an effective force as shown in Fig. 5. The propulsive force is the sum of drag force vectors to the moving direction in (1). It can be realized by changing frequency f1, f2 of the electric voltage applied on the ICPF actuators that the moving motion in the directions (forward, right turn and left turn) as shown in Table I.

The developed micro robot has a solenoid and two permanent magnets. It can change the body posture by adjusting the center of gravity as shown in Fig. 6.

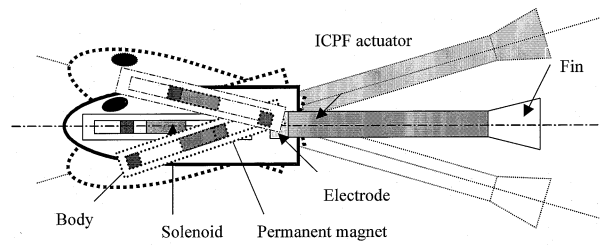


Fig. 6. Adjusting mechanism of the micro robot posture.

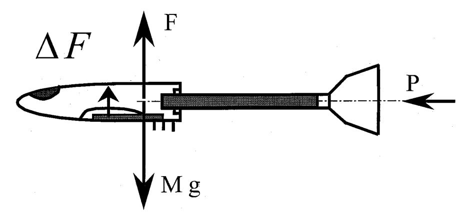


Fig. 7. Floating mechanism of the micro robot.

The developed micro robot has a buoyancy adjuster driven by the ICPF actuator. The ICPF actuator has the characteristic that when the frequency of the applied voltage is low less than 0.3 Hz, water around the ICPF surface is electrolyzed, so water bleb on both sides of the ICPF surface is generated. In result of the change of body volume, and floatage of the micro robot can be controlled. The floating mechanism of the developed micro robot is shown in Fig. 7

$$P = -\frac{1}{2} C_d \rho A |V_k| V_k \tag{1}$$

where C_d is drag coefficient based on wetted surface area A. ρ is the density of water. V_k is the speed in moving direction.

We know that the floatage of the micro robot is

$$F = \rho \times V_a \tag{2}$$

where V_a is the total volume of the micro robot. At first, the weight Mg is a little larger than the floatage F and the micro robot is sinking downward in water. When water around the ICPF surface is electrolyzed, the generated bleb adsorbs on both side of the ICPF actuator and it increases the total volume of the micro robot by Δv. It also increases the floatage by ΔF

$$\Delta F = \rho \times \Delta v. \tag{3}$$

We observed that the volume of the generated bleb could be controlled by changing the frequency and the amplitude of the applied voltage. On the condition of (4)

$$\Delta F = Mg - F. \tag{4}$$

it stops sinking and is suspended in water. When

$$\Delta F > Mg - F \tag{5}$$

it begins to float upward. When the frequency of the applied voltage is low, less than 0.3 Hz, electrolysis begins to be obvious and the larger the amplitude of voltage applied, the more the volume of the generated bleb will be.

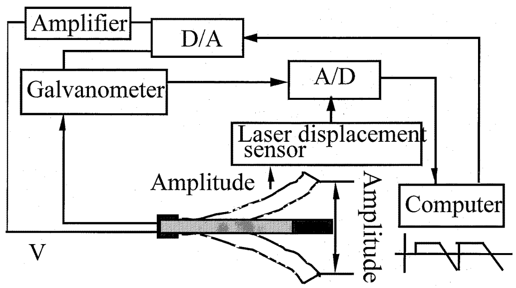


Fig. 8. Measurement system.

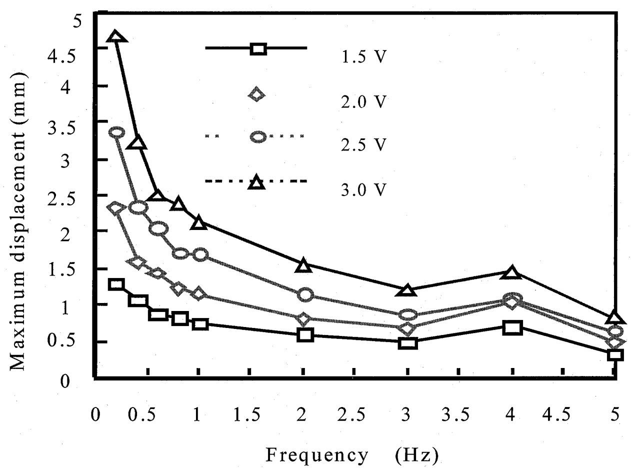


Fig. 9. Maximum displacement (in air).

IV. Characteristic Measurement

A. Measurement System

A computer can control the electric voltage set onto the ICPF actuators. The electrical current is measured by a galvanometer. The bending displacement of a fin at the point of the front end is measured by a laser displacement sensor. The bending amplitude of a fin can be obtained driven by an input voltage as shown in Fig. 3. The measurement system is shown in Fig. 8

B. Characteristic of a Fin of Micro Robot

By using the measurement system as shown in Fig. 8, the following characteristics are measured. First, we measured the maximum displacement of a fin in the center point by changing the frequency of input voltage as shown in Fig. 9 in air. Second, the maximum current is also measured by changing the input voltage.

The experimental results are shown in Figs. 9 and 10. From these experimental results, it is known that the maximum displacement is in inverse proportion to the frequency of the input voltage, and the maximum current is nearly proportional to the input voltage, respectively.

V. Prototype Fish-Like Micro Robot

The prototype of developed micro robot using the ICPF actuator is shown in Fig. 3. The specification of the micro robot is 10 mm in width and 45 mm in length (body 15 mm without tail) as shown in Table II. The body of micro robot is mainly made of wood material for lightweight.

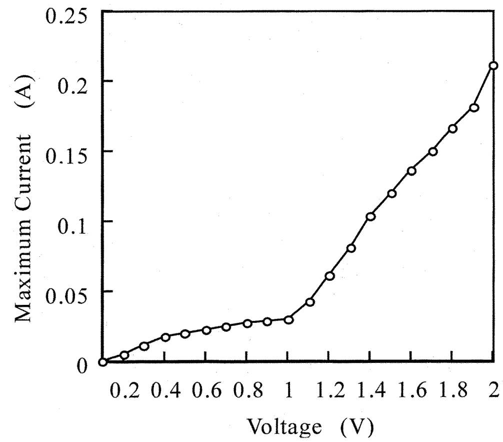


Fig. 10. Maximum electric current (in air).

TABLE II
Specifications of the Prototype Micro Robot

Size	10mm*45mm
Weight	0.76g
Material	Wood
Actuator	ICPF Actuator (0.2*3*15)
Power supply	Electricity (e.g.4V, 0.15A)

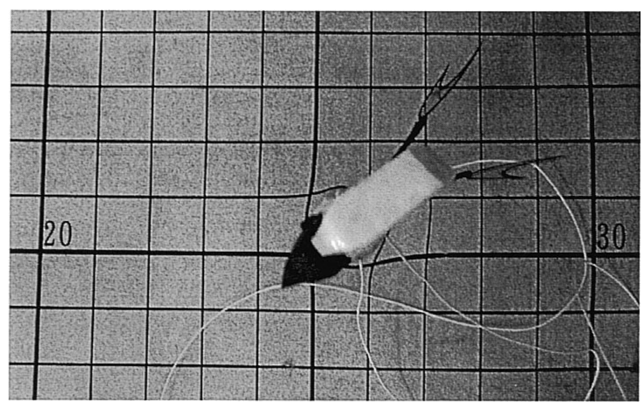
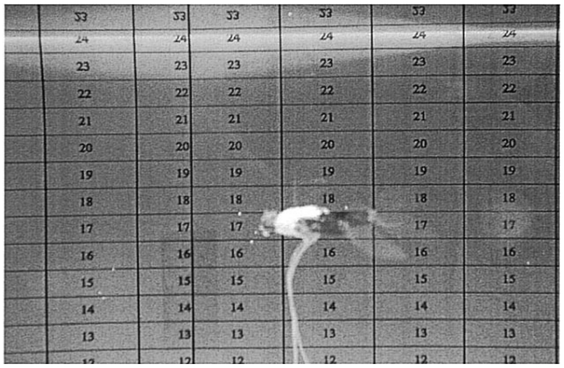


Fig. 11. Floating motion in water surface.

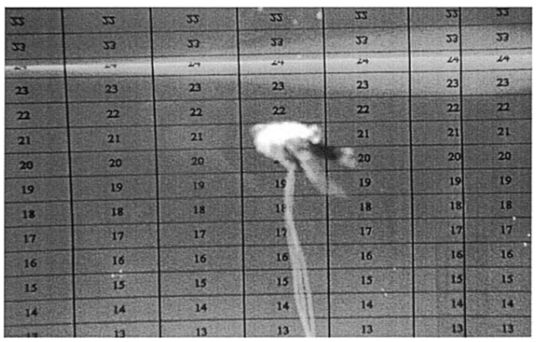
In order to verify the mechanism of the micro robot, we carry out the swimming experiments in three directions with three degrees of freedom (DOF) in water by changing the voltage frequency. Fig. 11 shows the swimming motion in the water surface. Fig. 12 shows the swimming motion in the vertical direction reaction in water by changing buoyancy of the micro robot.

VI. Experimental Results

We made the swimming experiments of the prototype micro robot using a measurement system shown in Fig. 13. The propulsive forces for various frequencies were measured using a laser displacement sensor, an electric balance and a copper beam. The copper beam is soft enough to be bent by the propulsive force. The electric balance is used for the force evaluation. We also measured the swimming speed and floating speed of the micro robot for various frequencies using a high-speed camera.



(a)



(b)

Fig. 12. (a) Initial position of the floating motion. (b) Final position of the floating motion of the micro robot.

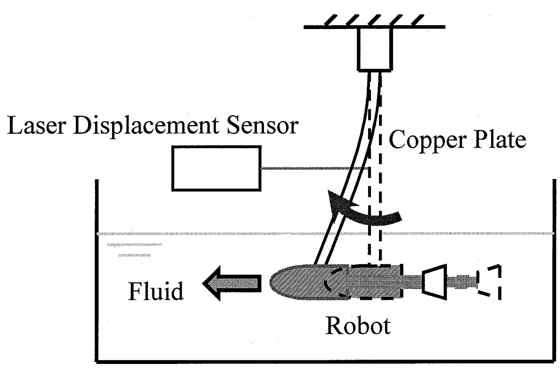


Fig. 13. Measurement system of propulsion.

The average value of over 20 data is used as the final test data. By changing the frequency from 0.2–5 Hz at 2.5 voltage input, the experimental results of average propulsive force, and average speed are shown in Fig. 14. Experimental results show that the moving speed 1.3 mm/s ~ 5.21 mm/s can be obtained by changing the voltage frequency. Fig. 15 shows the floating speed for the micro robot by using a high-speed camera. From the experiment results, it can be known that changing the voltage frequency can control the floating speed of the micro robot in vertical direction.

VII. Conclusion

Fish-like underwater micro robot is expected to become increasingly popular in the medical practice, both for diagnosis and for surgery. It is our purpose to develop an underwater micro robot that has the characteristics of flexibility, driven by a low voltage, good response and safety in body.

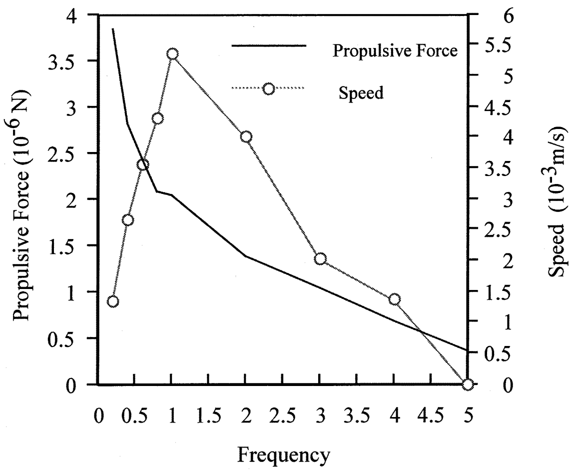


Fig. 14. Experimental results of swimming speed (2.5 V).

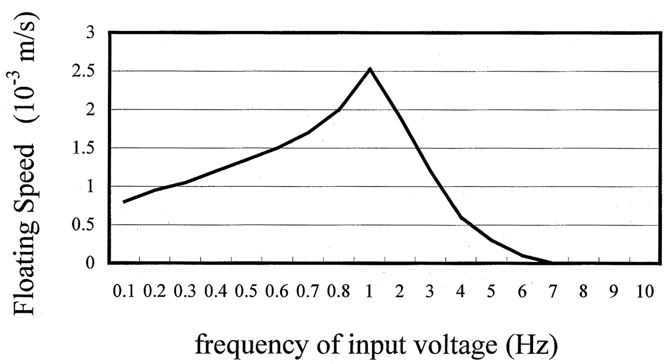


Fig. 15. Experimental results of floating speed (2.5 V).

In this paper, we propose a new prototype model of an underwater micro robot in water using the ICPF actuator. It has two tails with a fin driven respectively, a body posture adjuster, and a buoyancy adjuster. We also discussed the structure, motion mechanism. Characteristic of the micro robot is measured by changing the frequency of input voltage from 0.1–5 Hz in water and the amplitude from 0.5–10 V.

The research illustrates the following.

1) The structure of the underwater micro robot is effective;
2) The swimming speed can be controlled by changing the frequency of the applied voltage;
3) The moving motion in the directions (forward, right turn, and left turn) can be realized by changing frequency f1, f2, and the amplitude of the electric voltage;
4) The moving motion in the vertical direction, and the floating speed can be controlled by changing the frequency and amplitude of the applied voltage on the buoyancy adjuster.

In the future, we will do optimum design and energy supplying with wireless for the micro robot. It will be very useful for in-pipe inspection in industrial application and for microsurgery of blood vessel in minimum invasive medicine.

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