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Development of Flexible Underwater Robots with Caudal Fin Propulsion

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Abstract— **Fish type underwater robots has a lot of possibilities such as good mobility and high efficiency. Most of the fish type robots developed up to now have complicated mechanisms with complicated motion control. It results in that the structure and the movement of robots are different from that of fishes. The purpose of our work is to develop creature-like flexible underwater robots by using piezoelectric fiber composite. Compared with conventional artificial muscular underwater robots, powerful underwater robots with a very simple structure can be composed. This paper describes the development of a flexible underwater robot with caudal fin propulsion, which can generate large propulsive force and move at high speed. Besides, by utilizing the large propulsive force, pitch and roll motions are realized by attaching two pectoral fins to the robot.**

I. INTRODUCTION

In recent years, underwater robots come to be used for exploration, observation, research, and salvage.

Underwater creatures are capable of high movement performance in water and it has various forms, so it can be said that underwater robot design based on the movement mechanism of the underwater creatures is an effective method.

Over the past few years, many researches have been done on developing fish type robot as one form of underwater robot based on underwater creatures' swimming mechanism[1]-[3].

Most of the fish type robots developed up to now have complicated mechanisms using motors combined with cranks etc., and the control of the robots is complicated also[4],[5]. Furthermore, the movement by the robots is a mechanical one, lack of flexibility and fluency. Therefore, it is thought that interaction between the robots and the fluid differs from that of fishes and this kind of robots doesn't benefit the advantage of the fishes enough. Therefore, it is necessary to mimic not only the swimming mechanism but also the structure.

One approach to mimic the structure of fishes is to utilize new type of actuators so-called artificial muscle[6]-[9]. Although the new actuators used in those robots are potential ones in the future, one main problem of those actuators is that the power output is too small for practice.

As one new actuator to solve the power problem, piezoelectric fiber composite is noticed recently. The new type of piezoelectric fiber composite is flexible with large displacement. Compared with conventional artificial muscles, piezoelectric fiber composite can be used for composing powerful underwater robots with a very simple and compact structure. For example, an underwater robot can be made to behave like a genuine fish with only one piece of piezoelectric fiber composite and a thin structural plate[10]. For such a structure, a flexible and fluent motion can be realized and it can benefit more mimic advantages like a fish. Besides, such structure has the advantages of reduced fluid resistance and can be utilized in narrow space in underwater operation. In addition, due to high efficiency of energy converting by piezoelectric fiber composite, underwater robots with high speed and efficient motion can be realized. Besides, because piezoelectric fiber composite can be used for actuating, sensing and energy harvesting, intelligent underwater robots with intelligent control of motion as well as energy can be realized also. Those motivated us to apply piezoelectric fiber composite for underwater robots. We have developed underwater robot by body meandering motion, which is capable of fast motion(0.32m/s) and planar motion already[10].

To enhance the performance of the underwater robot using piezoelectric fiber composite, the realization of higher speed motion and three dimensional motion is considered in this paper. For this purpose, a underwater robot with caudal fin propulsion is proposed to achieve larger propulsive force and large speed. By utilizing the large propulsive force, pitch and roll motion can be realized by attaching two pectoral fins to the robot. First, the basic feature of piezoelectric fiber composite is introduced in section II. And basic principle for underwater robots is described in section III. A robot with caudal fin propulsion based on the principle and performance evaluation experiments are described in section IV. And the robot with a caudal fin and two pectoral fins capable of pitch and roll motion is introduced in section V. Section VI concludes the result.

II. PIEZOELECTRIC FIBER COMPOSITE

A. *Piezoelectric fiber composite and Macro Fiber Composite*

One typical and new piezoelectric fiber composite is the Macro Fiber Composite (MFC) developed by NASA[11]. Fig.1 shows the structure of MFC to be used as the actuator of the underwater robot. Because of structural features such as rectangular piezoceramic fibers and interdigitated

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electrode pattern on the polyimide film, this structure yields better flexibility and impact response, and a higher level of strain than conventional piezoelectric actuators. It expands and contracts in the direction of the fibers when a voltage (+1500V∼-500V) is applied.

B. *Actuation characteristic of MFC*

If a simple MFC sheet is used, the displacement as well as the force produced by the MFC is too small to drive a object such as underwater robot. Therefore, it is necessary to combine the MFC sheet with a structure so that resonant mode can be utilized for the desired motion to obtain large displacement.

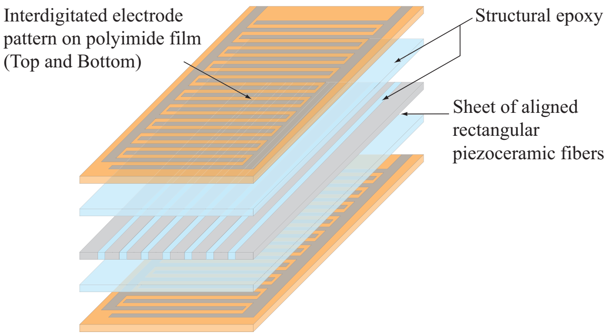
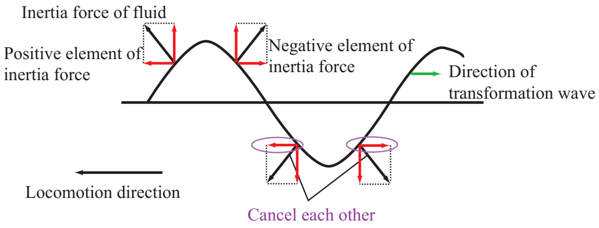


Fig. 1. Structure of Macro Fiber Composite

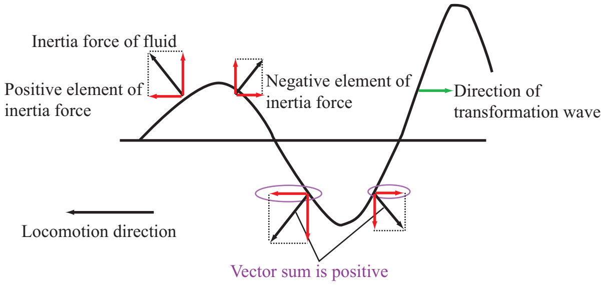
III. PRINCIPLE FOR UNDERWATER ROBOTS

Creatures that have a long and slender shape (cylindrical object) or a thin and long ribbon shape (belt object) move forward by making transformation waves generated by a meandering motion. The transformation is obtained by the bending moment generated from the muscles along the body axis. In cylindrical objects where the height, width or diameter is small compared with the body length, it is known that slender body theory holds. A transformation towards the rear of the body has little influence to the front end. The fluid force that works at a certain length is decided only by the cross-section shape and crossing velocity[12]. The transformation wave is sent to the rear of the body. Fig.2 shows the inertia force for (a) the meandering motion case of constant vibration amplitude and (b) the meandering motion case of increased vibration amplitude. Inertia force from the apparent increase in mass of the fluid due to transformation of the body cancels each other in Fig.2 (a) but becomes a propulsive force in (b).

Slender body theory also approves for slender body fishes such as river fishes. These fishes use propulsion by caudal fin transformation together with body transformation. For this case, higher acceleration and higher efficiency can be achieved comparing with cylindrical objects[12]. In our previous work, we mainly considered the meandering motion of cylindrical objects[10]. However, because the amplitude of transformation wave that made by slender body is narrower than that by cylindrical object, the propulsion by caudal fin is more useful for the case using actuators with small displacement, such as piezoelectric fiber composite.

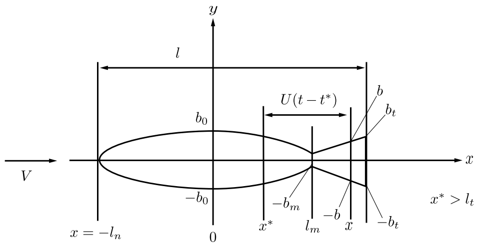


(a) Case of constant vibration amplitude

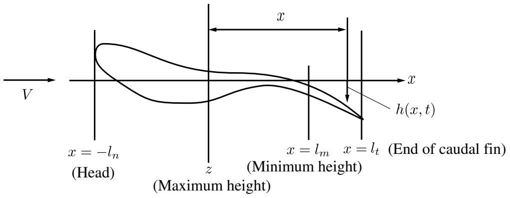


(b) Case of increased vibration amplitude

Fig. 2. Inertia force according to transformation wave movement



(a) Side surface



(b) Plane surface

Fig. 3. Coordinate system of slender fish

In Fig.3, lift distribution in body line direction of a slender object moving toward $-x$ at velocity V can be calculated from the pressure difference Δp that is the change of kinetic momentum in y directional. Equations (1) and (2) show the relations corresponding to the period before the point where the body hight is maximum and the period of caudal fin.

$$l(x,t) = \int_{-b}^{b} (-\Delta p) dy = -\frac{d}{dt}\left\{A_{33}(x) w(x,t)\right\}; \qquad (1)$$
$$(-l_n < x < 0)$$

$$l(x,t) = -\frac{d}{dt}\left\{A_{33}(x)w(x,t)\right\} + w^*\frac{d}{dt}\left\{A_{33}(x)\right\}; \quad (l_m < x < l_t) \tag{2}$$

where,

$$A_{33}(x) = \rho\pi b^2(x)\gamma \tag{3}$$

$$w(x,t) = \frac{d}{dt}h(x,t) = \left(\frac{\partial}{\partial t} + V\frac{\partial}{\partial x}\right)h(x,t) \tag{4}$$

$$A_{33}(-l_n) = 0 \tag{5}$$

$$\left|\frac{\partial h}{\partial x}\right| \ll 1 \quad and \quad \left|\frac{\partial h}{\partial t}\right| \ll V \tag{6}$$

$A_{33}(x)$ is added mass, ρ is fluid density, γ is coefficient of added mass. And w^* is the velocity of the vortex come from the end of caudal fin at an arbitrary position after the point with maximum height $x = x^*$ $(0 < x^* < l_m)$, can be defined as

$$w^* = w(x^*, t^*) \tag{7}$$

$$t^* = t - (x - x^*)/V \tag{8}$$

Assume that the slender body theory holds, distribution of lift between the points with maximum height and minimum height is

$$l(x,t) = -\frac{d}{dt}\left\{A_{33}(x)w(x,t)\right\}; \quad (0 < x < l_m) \tag{9}$$

Propulsion force T, consists of the part due to the above-mentioned of distribution of lift and the part by suction force that works at the front edge (T_s), can be calculated by

$$T = \int_{-l_n}^{l_t} l(x,t)\frac{\partial h}{\partial x}(x,t)dx + T_s \tag{10}$$

where,

$$T_s = \int_{-l_n}^{0}\left\{\frac{1}{2}w^2\frac{\partial A_{33}}{\partial x}\right\}dx + \int_{l_m}^{l_t}\left\{\frac{1}{2}(w-w^*)^2\frac{\partial A_{33}}{\partial x}\right\}dx \tag{11}$$

The suction power that works at the front edge is generated because the flow around the body of fish changes by the movement of the caudal fin, and flow velocity becomes fast at the front edge. Usually, the effect of this part is small for the slender object. Therefore, first term in equation (10) is dominant.

From the first term in the equation, it is known that the following conditions are important to achieve larger propulsive force in the case of the slender object.

1) The velocity of the transformation wave must be larger than that of the locomotion velocity

2) Body height toward the tail should be changed and should be decreased at the stem of caudal fin

3) The amplitude of motion toward the tail should be increased

4) For the fin, maximum height and maximum amplitude of motion should be located at the end of caudal fin

IV. ROBOT WITH CAUDAL FIN PROPULSION

First, a prototype of underwater robot with caudal fin propulsion is designed based on the principle described in last section.

A. Mechanism

Fig.4 shows the configuration of the underwater robot. Two pieces of MFC are pasted on each side of the robot body made by carbon plate (thickness 0.3mm). Using two pieces of MFC can achieve symmetric drive and increase the motion amplitude of caudal fin to achieve larger propulsion force. The shape of caudal fin uses the trout that is slender body fishes, and the aspect ratio is 2.0. Besides, by driving the two pieces of MFC with different input waves, turning motion can be realized. A weight is adhered to the head to constrain its movement. Then the amplitude of first vibration mode can be increased toward the tail by constraining the amplitude of the head end, similar to that of a cantilever. The height changes toward the tail and becomes smallest at the point where the caudal fin attaches to the body. To stabilize the body in water vertically, a low density material is adhered to the top of the body as a float. The developed prototype is shown in Fig.5. Single direction propulsive force is obtained by applying a pulse-wave voltage to MFC. The specification of the robot is shown in Table I.

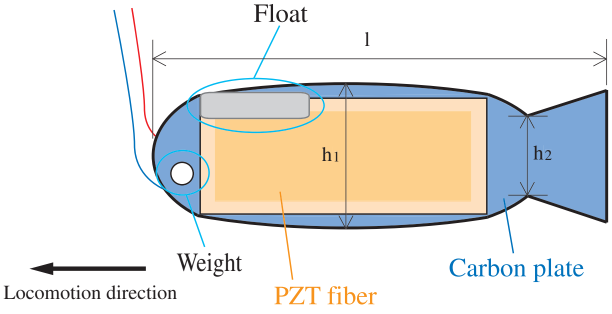


Fig. 4. Mechanism of the underwater robot

B. Locomotion velocity

The locomotion velocity of the underwater robot is measured by high speed camera. Fig.6 shows the experiment result. Maximum locomotion velocity is 0.72m/s (4.3BL/s) at the driving frequency of 18Hz. BL is body length. This value

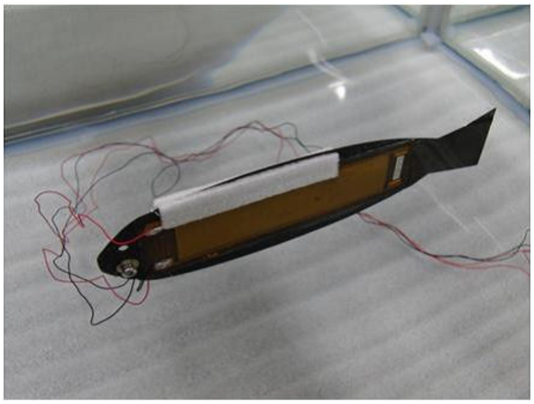


Fig. 5. Prototype of underwater robot

TABLE I
SPECIFICATION OF UNDERWATER ROBOT

Length$l$	167mm
Maximum heighth_1	55mm
Minimum heighth_2	30mm
Weight	15.98g
MFC type	M8528P1 d33×2
MFC overall dimensions	110mm×43mm
MFC active area	85mm×28mm
Material for adhering	Carbon plate 0.3mm
Adhesion bond	Epoxy Adhesives DP460

is more than twice that(0.32m/s,2.9BL/s) of our previous robot[10]. Locomotion velocity increases with increasing drive voltage, but falls in every 5Hz.

(experiment conditions)

Voltage range	$+1500V \sim -500V$
Frequency	1Hz∼25Hz
Drive voltage wave form	pulse

It is known that locomotion velocity reaches maximum because the motion of the robot reaches the resonant vibration in the fluid. Also, it is clear that it is possible to control the locomotion velocity by adjusting the frequency of input wave.

C. Propulsive force

We measured the propulsive force while changing the frequency. The propulsive force is measured by a force gauge (load cell of single axis) fixed to the upper part of a stick with rotation axis whose lower side is contacted to the robot.

(experiment conditions)

Voltage range	$+1500V \sim -500V$
Frequency	1Hz∼25Hz
Drive voltage wave form	pulse

The experiment result is plotted in Fig.6. The maximum propulsive force is 0.18N at the driving frequency of 18Hz. It is known that maximum propulsive force is obtained when the motion of robot is maximum at resonant frequency.

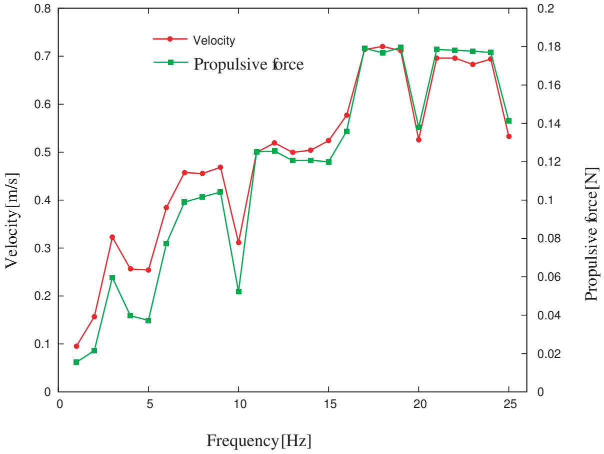


Fig. 6. Locomotion velocity and propulsion force

D. Efficiency

Propulsion efficiency η_p is calculated from (12) by locomotion velocity V, average of propulsion force $\bar{T}$, and electric power W.

$$\eta_p = \frac{\bar{T}V}{W} \tag{12}$$

To calculate efficiency, electric power was measured by measuring the voltage and current to MFC. Fig.7 shows the measured result. Electric power increases when the frequency of drive voltage increases. Efficiency can be calculated by above results, and its result is shown in Fig.8.

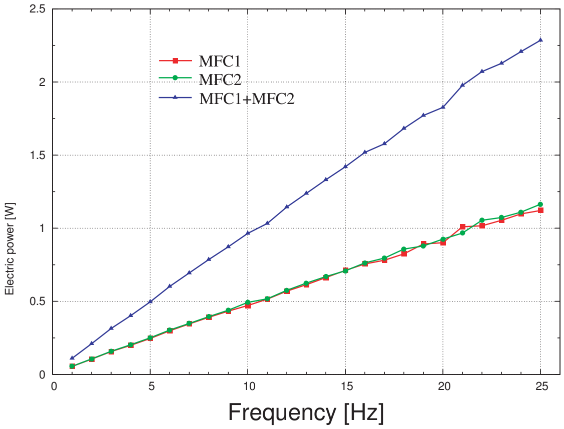


Fig. 7. Electric power of underwater robot

Maximum value of propulsion efficiency is 8.11% at the driving frequency of 17Hz.

E. Discussion on locomotion of the robot

In Fig.6 and Fig.8, there are some minimum points. We observed the motion of the underwater robot by high speed camera. Fig.9 shows the vibration shapes of the robot during the locomotions at 10Hz and 18Hz. From the figure, it is found that (a) the amplitude of end of caudal fin is large in the mode shape of 18Hz, but (b) the amplitude of the end

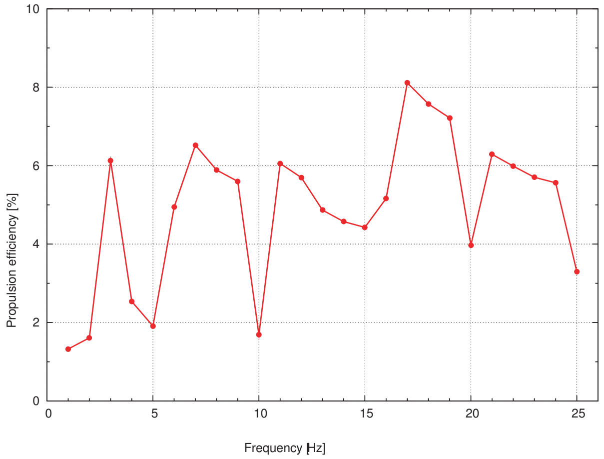


Fig. 8. Efficiency of underwater robot

of caudal fin is small in the mode shape of 10Hz. Therefore, those minimum points are due to the excited mode shapes which cannot contribute larger propulsive force.

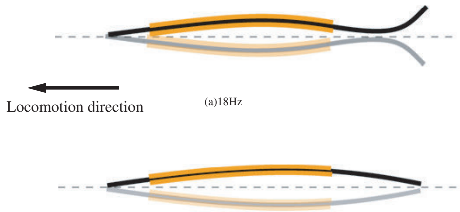


Fig. 9. Mode shape of vibration

F. Turning motion

Turning motion can be achieved by applying drive voltage with bias to the MFCs of the underwater robot. Fig.10 shows experimental result of turning speed, where bias is set to 1000V. Maximum turning velocity is 26.9deg/s at the driving frequency of 17Hz. This value is three times of that(9.2deg/s) of our previous robot[10].

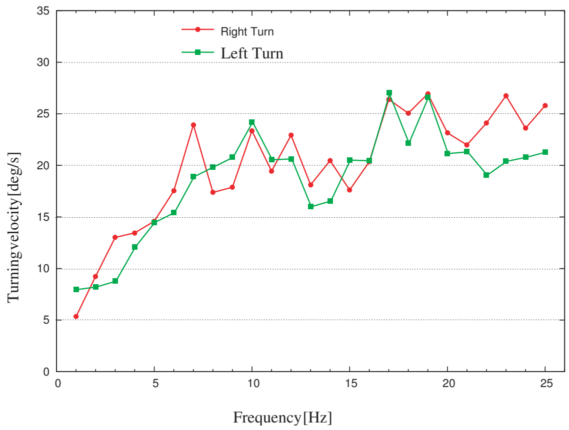


Fig. 10. Turning speed of underwater robot

The movie of the planar motion by the robot can be referred to [13].

V. REALIZATION OF PITCH AND ROLL MOTION

The developed underwater robot are capable of more fast planar motion as described in last section. As the performance extension, three dimensional motion is to be realized in this section. To realize it, pitch motion and roll motion besides the planar motion are considered. To achieve these motions, our proposal is to add two pectoral fins to the underwater robot. The two pectoral fins are used to change the attack angles of pectoral fins, and then to realize the pitch and roll motions utilizing the propulsive force generated by the caudal fin. A MFC of 85mm×7mm is used for each pectoral fin, to realize large attack angle. The developed pectoral fin mechanism is shown in Fig.11. Two fins are located near to the center of gravity, as shown in Fig12.

Fig. 11. Pectoral fin

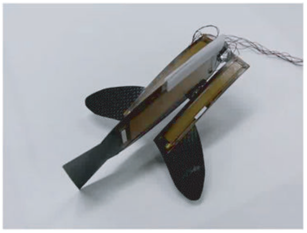


Fig. 12. Overall view of robot

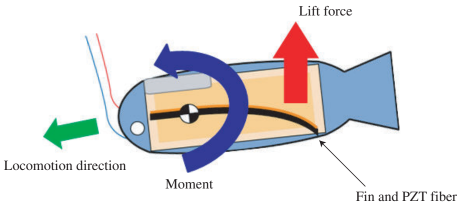
A. Drive control for pitch and roll motion

The basic control method for pitch and roll motions is shown in Fig.13. For the case of Fig.13(a), two pectoral fins are driven to be bended down or up. When the robot moves, a lift is generated by the flow of water and the amount of the lift depends on the propulsive speed and the attack angle of the pectoral fins. And because the center of the lift is located near to the tail, a moment which makes the robot rotate in pitch direction is generated. if the pectoral fins are bended down, the robot will go down. Otherwise, it will go up. Therefore, pitch motion can be realized. On other hand, For the case of Fig.13(b), one of the pectoral fins is driven to be bended down, the other is driven to be bended up symmetrically. Two lifts with same value but opposite direction are generated by the two pectoral fins and a moment which makes the robot rotate in roll direction is generated. Therefore, the roll motion can be realized.

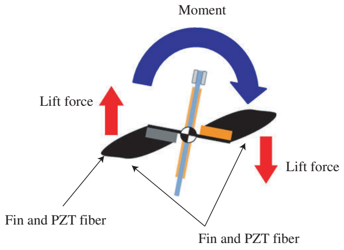
B. Results

Fig.14 shows the experimental result of the speed of pitch motion. Pectoral fins are driven by constant voltages of 250V, 500V, 750V, and 1000V.

(experiment conditions)	
Voltage range	$+1500V \sim -500V$
Frequency	1Hz∼25Hz
Drive voltage wave form	pulse



(a) Pitch motion



(b) Roll motion

Fig. 13. Pitch and roll motion

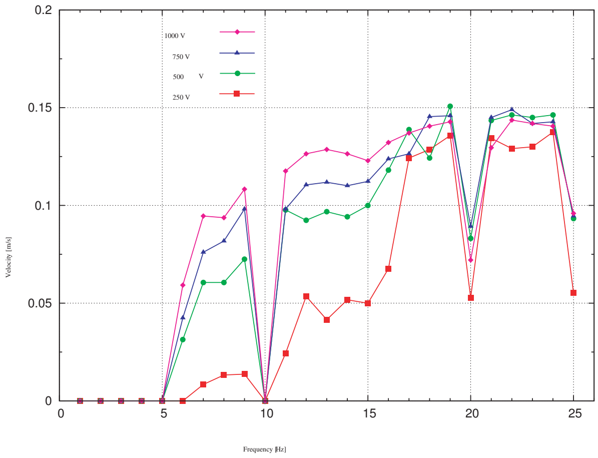


Fig. 14. Dive velocity of underwater robot

Maximum speed is 0.15m/s at the drive frequency of 19Hz. There are exists some minimum points similar to those in Fig.6 and Fig.8.

It is also confirmed that the roll motion has been realized by this prototype.

The movie of the pitch and roll motion by the robot can be referred to [13].

VI. CONCLUSIONS

In this paper, underwater robot capable of more fast and three dimensional motion has been developed successfully by using piezoelectric fiber composite. One of the next tasks is to control the robot to move according to the specified trajectory in more complicated environment. Another is to improve the efficiency by optimizing the propulsion control and introducing the sensor function of the piezoelectric fiber composite.

We will research more various movements in water based on a swimming mechanism and a flexible structure in the future.

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