Research on a Sea Snake Robot

Hiroshi Shiozaki*, Etsuro Shimizu* and Masanori Ito*

*Tokyo Univ. of Marine Sci. & Tech.

(Tel : +81-3-5245-7300; E-mail: hshioza@e.kaiyodai.ac.jp)

Abstract: Since a snake achieves various movements just by a slender body, the mechanism of it is very amazing Many researches have been focusing on a snake like robot and have done for it on the ground. However the meander motion of the snake not only can be done by ground creatures, but also can be done by a water creature such as a sea snake or an eel. Therefore, the purpose of our research is to develop an autonomous underwater robot like the sea snake. As an approach to this goal, we develop an experimental sea snake-like-robot for examining basic characteristics, including propulsion, a turning and other performance. Our developed robot is composed of the head and 4 bodies. Each body equips one servomotor, which is operated with pulse signal. In the head unit, 1-chip-microcomputer, which generates the servomotor control signal for realizing a snake motion and the battery, is equipped. Our robot is covered with a rubber film for the waterproof. Using our developed robot, characteristics of the snake-like-robot moved in water are examined.
.

Keywords: snake-like-robot, biomimetics, experimental verification, robotic locomotion

1. INTRODUCTION

A machine made by human hasn t yet achieve high functional movements, which can be easily done by a living creature, until now. Therefore, understanding the principle of the movement of a living creature and using it technologically are very useful for developing a new kind robot. In this paper, we focus on a living creature with slender body like a snake. A snake can generate an extraordinary variety of motions. For example, changing the slender body shape to adjust to rugged surface when it creep on the ground, changing the slender body shape like a bridge when it gets over the gap, changing the body shape to wrap around a object when it try to grip the object, and so on. Namely, since the snake achieves various movements just by a slender body, the mechanism of the snake is very amazing. However, most researches about a snake like robot have focused on the movement of the ground [1],[2],[3]. But, the meander motion of the snake not only can be done by the ground creature, but also can be done by a water creature such as a sea snake or an eel. Since the direction of the wave changes rapidly when the wave is sent to the slender body and it advances, go ahead and go astern are easily switched. In other words, the dynamic positioning or the position keeping is very easy work for these creatures. If we can construct the snake like robot, it is possible to create an autonomous underwater robot, which can act in narrow waters. A detailed position control is needed if the snake like robot is used in such a place. Although the sea snake-like-robot has possibility to become an excellent underwater robot, it will be a complicated research compared with the research about the ground snake-like-robot. Therefore, the purpose of our research is to develop an autonomous underwater robot like the sea snake. As an approach to this goal, we develop an experimental sea snake-like-robot for examining basic characteristics, including propulsion, a turning and other performance. Our developed robot is composed of the head and 4 bodies. Each body equips one servomotor, which is operated with pulse signal. In the head unit, 1-chip-microcomputer which generates the servomotor control signal for a snake motion and the battery is equipped. By those four servomotors and 1-chip-microcomputer, our developed robot can simulate many moving patterns. Our robot is covered with a rubber film for the waterproof. Using our developed robot, characteristics of the snake-like-robot moved in water are examined.

2. PRINCIPLE OF PROPULSION

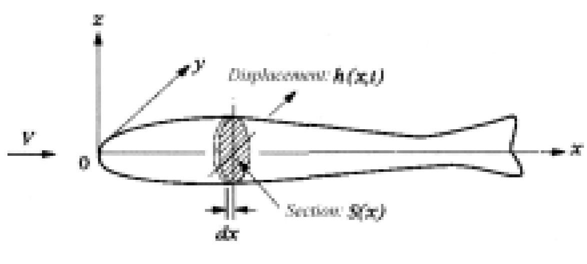

Fig.1 Analysis of swim by slender body theory

In the propulsion with slender body like the sea snake, there is an analysis method applying "slender body theory" below [6][7]. Fig. 1 shows the coordinate system where the starting point is fixed to the head of the sea snake of length *l*. The sea snake is oscillating in the direction of *y* as a symmetry plane in *xz-plane* and the moving constant speed *V*. When *y* direction displacement in arbitrary section $S(x)$ along the body axis *x* is defined as $h(x,t)$, *y* direction velocity of the surrounding fluid caused by the motion is, as the sum of a non-stationary element and the convection element, as follows:

$$v(x,t) = \partial h/\partial t + V\,\partial h/\partial x \quad (1)$$

If the virtual mass per unit length in the section *S* is defined as $m_a(x)$, *y* direction momentum and the kinetic energy in the section become $m_a v dx$ and $(1/2)m_a v^2 dx$ respectively. Therefore, since it is equal to the substance change in y direction momentum, the force necessary for the motion of this section is shown as follows:

$$F = -\left(\partial/\partial t + V\,\partial/\partial x\right) m_a v dx \quad (2)$$

If *F* is multiplied by the displacement velocity $\partial h/\partial t$ in the section, and it is integrated from *x*=0 to l, the power $P(t)$ that the sea snake gives to a surrounding fluid is as follows with Eq. (1) :

$$P=-\int_0^l F\cdot\frac{\partial h}{\partial t}=\int_0^l\frac{\partial h}{\partial t}\cdot\left(\frac{\partial}{\partial t}+V\frac{\partial}{\partial x}\right)m_a v dx$$
$$=\int_0^l\left(\frac{\partial}{\partial t}+V\frac{\partial}{\partial x}\right)\left\{\frac{\partial h}{\partial t}m_a v\right\}dx-\int_0^l\frac{\partial v}{\partial t}m_a v dx \tag{3}$$
$$=\frac{\partial}{\partial t}\left\{\int_0^l\frac{\partial h}{\partial t}m_a v dx-\frac{1}{2}\int_0^l m_a v^2 dx\right\}+V\left[\frac{\partial h}{\partial t}m_a v\right]_0^l$$

By integrating the above equation at time, the mean value of the necessary power is as follows:

$$\overline{P}=\frac{1}{T}\int_0^T P(t)dt \tag{4}$$

If this is executed, it is considered that the mean value the first term of the last equation in Eq.(3) obviously becomes 0. In addition, thinking about the distribution of the section in the direction of the axis of the sea snake that Figure 1 shows, it can be considered as follows:

$$m_a(0)=0 \qquad m_a(l)\neq 0 \tag{5}$$

Therefore, the last paragraph remains only the value in $x=l$, and becomes as follows, too:

$$\overline{P}=V\left\{m_a\overline{v\frac{\partial h}{\partial t}}\right\}_{x=l} \tag{6}$$

Because the power of the above equation divides into the kinetic energy invalidly discharged in the slipstream and the effective power that the sea snake is made to advance,

$$\overline{P}=\overline{T}V+\frac{1}{2}\left\{m_a V\overline{v^2}\right\}_{x=l} \tag{7}$$

As a result, the average thrust and the propulsion efficiency of the sea snake are calculated respectively as follows:

$$\overline{T}=\frac{1}{2}\left[m_a\left\{\overline{\left(\frac{\partial h}{\partial t}\right)^2}-V^2\overline{\left(\frac{\partial h}{\partial x}\right)^2}\right\}\right]_{x=l} \tag{8}$$

$$\eta=1=\frac{1}{2}\left\{\frac{\overline{v^2}}{\overline{v(\partial h/\partial t)}}\right\}_{x=l} \tag{9}$$

Next, as a motion of the body axis, it thinks about the progressive wave motion as follows:

$$h=f(x)g(t-x/c) \tag{10}$$

Where $f(x)$ is the amplitude distribution along the body axis of the progressive wave, and c is the sound wave velocity of the wave. If Eq.(10) is substituted for Eqs.(8),(9),

$$\overline{T}=\frac{1}{2}\left[m_a\left\{\left(1-\frac{V^2}{c^2}\right)f^2\overline{g'^2}-V^2f'^2\overline{g^2}\right\}\right]_{x=l} \tag{11}$$

$$\eta=1-\frac{1}{2}\left[\left\{\left(1-\frac{V}{c}\right)^2f^2\overline{g'^2}+V^2f'^2\overline{g^2}\right\}/\left\{\left(1-\frac{V}{c}\right)f^2\overline{g'^2}\right\}\right]_{x=l} \tag{12}$$

As a result of the above equations, it should be V/c 1 that the sea snake promotes efficiently. That is, the wave velocity c is always larger than the forward velocity V, and the inclination of the amplitude of the oscillation of the body axis in the point of the tail only has to become

$$f'(l)=0.$$

If $f'(l)=0$ is substituted for expression (11) and (12), as follows:

$$\overline{T}=\frac{1}{2}\left(m_a f^2\overline{g'^2}\right)_{x=l}\left(1-\frac{V^2}{c^2}\right). \tag{13}$$

$$\eta=\frac{1}{2}\left(1+\frac{V}{c}\right). \tag{14}$$

In this case, A and B as a function of c are shown in Fig.2 .

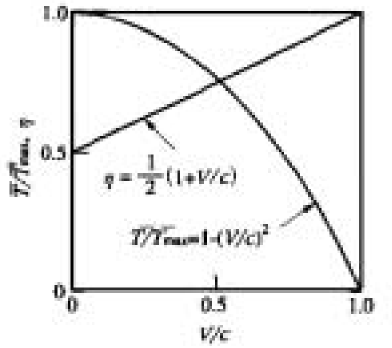

Fig.2 Thrust and Efficiency as a function of V/c

3. DEVELOPMENT OF SEA SNAKE RO OT

3.1 Model of sea snake robot

Model of snake robot is structured by the serial link system, and each link connects with active joints. This corresponds to the musculoskeletal system that the body of snake consists of the spine bone and the rivalry muscle group that accompanies it. Thinking about the two-dimensional motion on the plane as the most basic one, the winding angle for the meander motion around a vertical axis from the sliding surface. To add a friction characteristic necessary for the propulsion of snake robot, it is equipped with the passive wheel that rotates freely in the direction of rolling as shown in Fig.3.

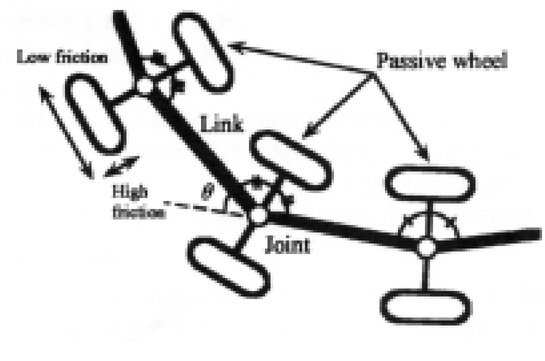

Fig.3 Model of snake robot on land[2]

On the other hand, if we consider the model of sea snake, it only has to connect the joint that basically does the winding movement as well as the model of the snake on land with the serial. However, the sea snake is moved in the fluid by pushing the fluid in the vertical direction to the body axis, the model like a ribbon of which surface area is small in the direction of the body axis and large in the vertical direction to the body axis is considered as shown by Figure 4. However it is impossible to do the flat on the structure of unit The model by whom the resistance in the vertical direction is increased to the body axis is regarded by attaching the fin in the unit.

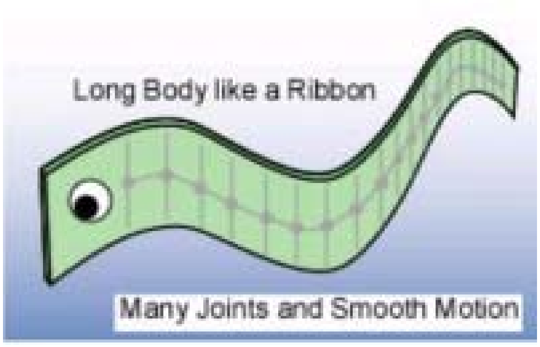

Fig.4 Model of sea snake robot[8]

3.2 Structure of sea snake robot

Figs. 5,6 shows the structure of the robot. This robot divides into the head equipping with the microcomputer and the battery and the body parts. The body parts are the same structural modules equipping with the servomotor and are connected with the vertical joints. To operate in water, the watertight structure has been achieved by covering the main body with the film made of a rubber. In order to stabilize posture, the fin is attached of the head part. The fin to increase the resistance is attached to the each body in the vertical direction of to increase the resistance. Moreover, this robot is also possible the meander movement on the ground by attaching of the passive wheel. Table.1 shows the specification of the sea snake robot.

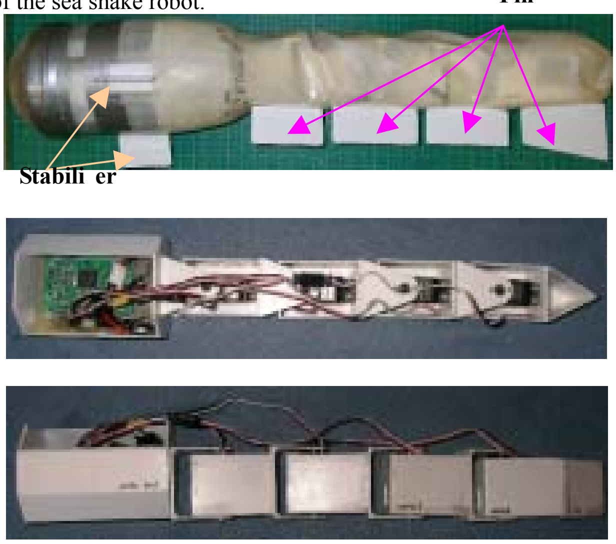

Fig.5 Structure of sea snake robot

Table 1. The specification of sea snake robot

Mode	Landscape	Under-Water
Length	440mm	473mm
Weight	430g	1790g
Joint	4	
Actuator	S3003 4	
Torque	0.4Nm(4.1kgfcm)	
Speed	0.19sec/60degrees	
CPU	H8/3048F	
Battery	Lithium-Polymer Battery 7.4V/1000mAh	

3.3 Waterproof

The sea snake robot sends the wave to the body and goes ahead, and thrust is generated only with the meander motion of the body. The waterproof seal is necessary for the rotation part to have to put out the rod that rotates infinitely from the hull outside in the ship etc. and to rotate the screw. However, such a seal mechanism is unnecessary for the swimming mechanism that can be only generated by the meander motion as the sea snake robot. Therefore, it is enough to seal up the entire body. However, in order to generate the wave by using the entire body for the sea snake robot, the body is always transformed. Therefore, it is necessary to cover the joint part with a flexible material that doesn t disturb the movement of the actuator. Then, the head was enclosed in the waterproof container that was able to remove the lid, and the body in the joint part was covered with the bathing suit made of rubber in this sea snake robot. And, both are firmly stuck together with the waterproof tape and have been sealed up. The rubber was the latex rubber of the liquid used by a special make-up etc.

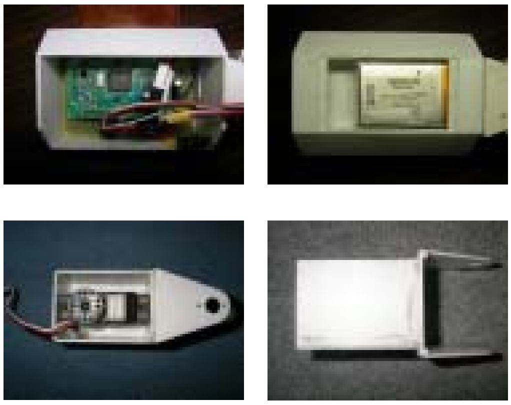

Fig.6 Details of each part

3.4 System configuration of robot

The servomotor used as the actuator can control the angle in every 20ms with giving the pulse signal of the width of 0.5ms-2.4ms. This robot used the single-chip microcomputer named H8 with the timer function to generate this pulse signal accurately. H8 can do the program development by using PC. C language was used for the program. Because the pin number 12, 14, 16, and 18 of the channels 1 of H8 are the output ports of the PWM signal using a built-in timer, H8 and the servomotor are directly connected of the control line of four servomotors. Since the PWM signal that controls the servomotor is generated by all programs built into CPU, an external circuit is unnecessary. Moreover, the power supply system divides one lithium Polymer battery system of 7.4V-1000mAh into two systems of 6V in CPU and 5V in servomotors in. The power supply stabilized respectively by using two three terminal regulators for the distribution of the power supply is supplied.

3.5 Control method

The meander movement of the snake has been achieved by giving the oscillation of the sine wave to each joint, and transmitting it backward applying a constant phase difference. Therefore, the control instruction like Eqs. (15)-(18) is given to each servo motor in this robot and the meander movement is generated

$$S_1 = A_1 \sin(2\pi f) + B \qquad (15)$$

$$S_2 = A_2 \sin(2\pi f - \theta) + B \qquad (16)$$

$$S_3 = A_3 \sin(2\pi f - 2\theta) + B \qquad (17)$$

$$S_4 = A_4 \sin(2\pi f - 3\theta) + B \qquad (18)$$

where A is amplitude（A_{max}=90deg）, f is frequency, θ is phase difference, B is bias（angle of deviation）.
The propulsive velocity can be controlled by changing each parameter of amplitude A, frequency f, and the phase difference θ. Moreover, the traveling direction is controlled with bias B.
The traveling direction is changed by moving a center value of the oscillation by putting the bias on the sine wave instruction that generates the meander movement as shown in Figure 6. When the bias is 0, the winding standard of the entire body is straight. However, the winding standard becomes by the bias being added like the circular arc, and the direction of propulsion changes into the direction where added the bias only at time to have added the bias. In a word, because it is possible that the direction control of the meander movement that seems to be difficult seemingly is divided into the sine wave instruction as the propeller and the bias value as the vertical rudder, and think about it, it is thought that the analysis of turning characteristics and the control of the turn angle are comparatively easy.

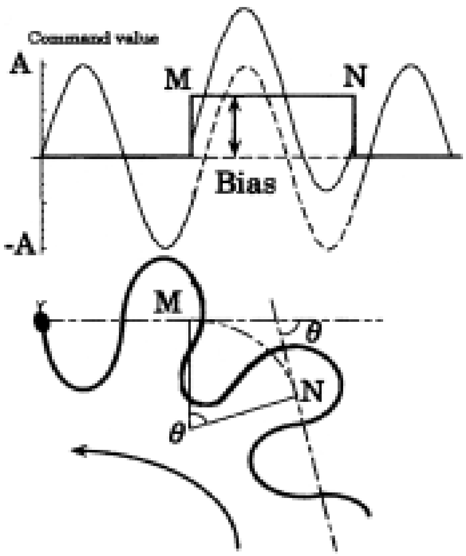

Fig.7 Control of traveling direction[2]

4. EXPERIMENT

4.1 Propulsive performance experiment

4.1.1 Experiment of frequency - velocity

Since the pulse width when the servomotor was driven was output by constant transfer rate, the frequency was changed by changing the data density for one wavelength output to the servomotor. And, the relation between the frequency and the moving velocity was examined. As experimental conditions:

- Phase difference: θ=30deg
- Amplitude: A_1=30*deg*, A_2=35*deg*, A_3=40*deg*, A_4=45*deg*

The time took to advance in the distance of 1.65 meters was m easured.

Table.2 Experiment data of frequency velocity

Frequency *f*(Hz)	No.1	No.2	No.3	Average	Velocity *V*(cm/s)
0.185	37.300	37.760	37.690	37.583	4.4
0.370	24.030	23.780	24.420	24.077	6.9
0.556	13.960	13.360	14.220	13.847	11.9
0.741	10.390	10.240	10.020	10.217	16.2
0.926	8.240	8.700	8.600	8.513	19.4
1.111	9.470	9.240	9.360	9.357	17.6
1.296	8.050	8.620	8.530	8.400	19.6
1.389	7.490	6.860	7.150	7.167	23.0
1.667	7.140	7.140	7.040	7.107	23.2
2.222	7.100	7.280	7.112	7.190	22.9

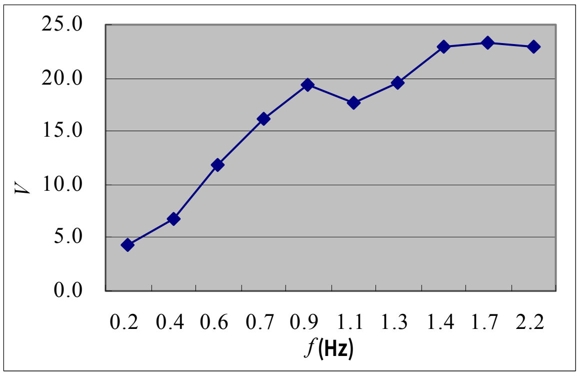

Fig.8 Graph of frequency velocity

Fig.8 shows the result of experiment. From the experimental result, we found that the frequency and the velocity are proportional under the frequency being equal to 1*Hz*. However, there is a sudden dip when the frequency exceeds 1Hz. The re ason is that the robot went under the water. Afterwards, ther e is proportional increase again and steady when the freq uency exceeds 1.4*Hz*. The reason is that the servo speed doesn t catch up with change of the angle. Moreover, the frequency is controlled by changing the data density of the sine wave instruction. Therefore, when the frequency is increased, it is necessary to generate the sine wave with a little number of data. Consequently, the error margin with a true sine wave grows, and the velocity doesn t increase either.

4.1.2 Experiment of phase difference - velocity

As experimental conditions:

- Frequency: *f*=0.93Hz
- Amplitude: A_1=30*deg*, A_2=35*deg*, A_3=40*deg*, A_4=45*deg*

The time took to advance in the distance of 1.65 meters was measured.

Table.3 experimental data of phase difference - velocity

Phase difference θ(deg)	No.1	No.2	No.3	Average	Velocity (cm/s)
0	25.73	26.72	27.03	26.493	6.2
30	8.240	8.700	8.600	8.513	19.4
45	7.410	7.300	7.430	7.380	22.4
60	7.76	7.77	7.48	7.670	21.5
90	18.96	17.72	17.65	18.110	9.1
120	60.02	59.2	61.3	60.173	2.7

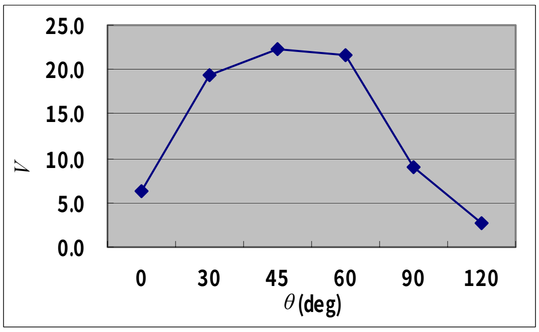

Fig.9 Graph of phase difference - velocity

From the experiment result, it was found that the maximum speed could be obtained when the phase difference was almost 45deg. Because the entire body became a phase difference like one wing when it was too small, it became inefficient. Moreover, the wave speed slowed more than the forward speed of the robot when the phase difference was too great, and it didn t advance.

4.2 Turn performance experiment

As experiment conditions:

- Frequency: $f = 0.93Hz$
- Phase difference: $\theta = 45deg$
- Amplitude: $A_1 = 30deg$, $A_2 = 35deg$, $A_3 = 40deg$, $A_4 = 45deg$

Table.4 experiment data of turn performance

	Turn-time(s)/Turn-diameter (cm)				
Bias (deg)	No.1	No.2	No.3	Average	Turn-velocity (cm/s)
10	22.7	22.6	28.1	24.5	24.1
	190	185	190	188.3	
20	8.99	9.02	8.88	9.0	31.7
	90	93	88	90.3	
30	8.89	8.75	9.1	8.9	18.0
	50	55	48	51.0	
40	8.28	9.63	8.73	8.9	9.8
	30	25	28	27.7	

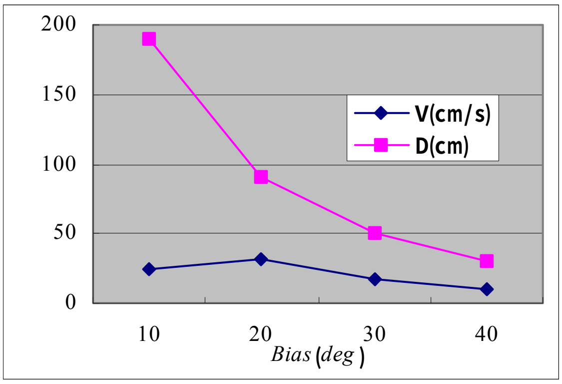

Fig.10 The graph of turn-performance

From the experiment result, it was found that the turn diameter was in inverse proportion to the bias and had surely become small. However, it had been understood that the turn speed didn t change too much even if the value of the bias changes. As a result, it is found that the bias contributes only to the control of the traveling direction. Figure 11 shows the appearance of the turn experiment.

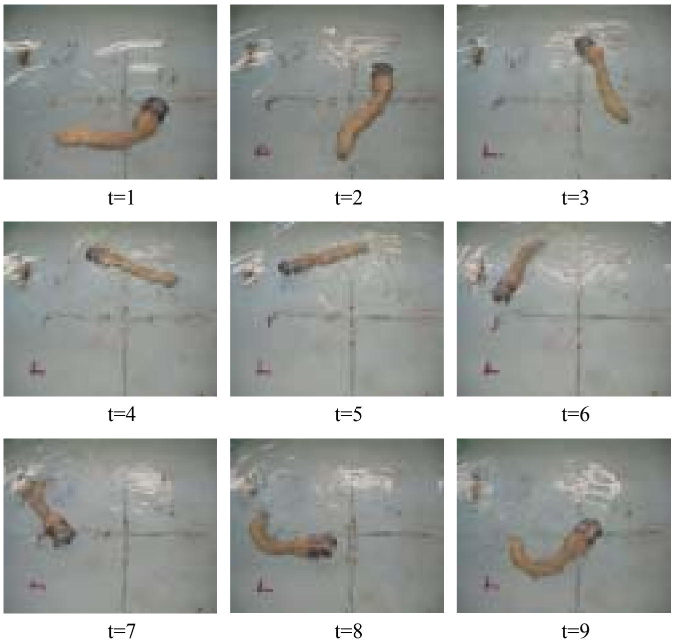

Fig.11 Appearance of turn experiment (bias = 20deg)

5 CONCLUSION

In this research, the snake robot that has been studied as a ground robot was applied as an underwater robot. As the first approach to this purpose, a propulsive principle of sea snake was studied, and the experimental sea snake robot was developed on the basis of it. And, a basic characteristic of its meander swimming was verified, and following results were obtained.

(1) The frequency of each joint motion and the velocity were almost proportional.

(2) Maximum speed was obtained when the phase

difference was 45deg.

(3) Consequently, it was found that the sea snake robot became the maximum speed when the frequency was 1.4Hz and phase difference was 45deg.

(4) The traveling direction was changed by moving the center value of the oscillation by adding the bias to the sine wave instruction that generated the meander movement. As a result of the turning experiment, it was found that the turning radius could be controlled. Moreover, it had been understood that the turn speed was not influenced too much by the bias. This showed no interference mutually by a basic sine wave and the bias

From these results, a basic characteristic necessary to use the snake like robot in water could be examined. Next, sensors are mounted into the robot, and the robot that moves autonomous is made. The gyro sensor is mounted to put the camera on the head of the robot and posture is controlled. Moreover, the sea snake robot that can move three dimensions is made from the combination of joints that rotate by mutually perpendicular planes.

REFERENCES

[1] F. Matsuno, “ Snake-like Robot－Super-biological ro bots and imitative biological robots－ ” ,*The Robotics Society of Japan*, Vol. 20, No. 3, pp. 261-264, 2002.

[2] G. Endo, K Togawa and S Hirose, Study on self-c ontained and terrain adaptive active cord mechanis m , *The Robotics Society of Japan*, Vol.18, No.3, pp.4 19-425, 2000.

[3] S. Hirose, E. F. Fukushima and S. Tsukagoshi, An Optimal Steering Control for the Articulated Body Mobile Robot , *The Robotics Society of Japan*, Vol.12 No.5, pp.759-765, 1994.

[4] T. Takayama and S Hirose Study on 3D active co rd mechanism with helical rotational motion , *The Robotics Society of Japan*, Vol. 22, No.5, pp.625-635, 2 004.

[5] K.A. McIsaac and J.P. Ostrowski “ Experimental of Verification of Open-loop Control for an Underwater Eel-like Robot ” *The International Journal of Robotics Research*,Vol.21, No.10-11, pp.849-859, 2002.

[6] Lighthill, J., *J. Fluid Mech.*, 9(1960), 305~317.

[7] 日本流体力学学会, 流体力学ハンドブック, (1987-7), 丸善, 758.

[8] K. Hirata, Development of Experimental Fish Robot , *Sixth International Symposium On Marine Engineering*, p.711-714, Oct. 2000.