2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Mechanism and Control of a Novel Type Microrobot for Biomedical Application

Shuxiang Guo[*1 *2]

[*1]*Faculty of Engineering, Kagawa University*

2217-20, Hayashi-cho, Takamatsu, 761-0396,Japan

[*2]*Harbin Engineering University, China*

guo@eng.kagawa-u.ac.jp

Qinxue Pan

Graduate School of Engineering

Kagawa University

2217-20, Hayashi-cho, Takamatsu, 761-0396,Japan

s05g521@stmail.eng.kagawa-u.ac.jp

Abstract - **A microrobot that can be moved along blood vessels has a great potential application for microsurgery. This paper discusses the development of a wireless microrobot that can be manipulated inside a tube using an external magnetic field. The model microrobot utilizes an electromagnetic actuator as the servo actuator to realize movement in biomedical applications. The structure, motion mechanism, and characteristic evaluation of a driving fin used for propulsion have been discussed. The fishlike fin movement can be controlled via frequency adjustments to the alternate magnetic field. Vertical movement of the microrobot can be stopped at a specified location. Experimental results indicate that the microrobot can be controlled upward, downward, and also be suspended in water using frequency adjustments. The microrobot has a rapid response, and can correspond to the dirt adhering to the inner wall. This device will play an important role in both industrial and medical applications such as microsurgery.**

Keywords - **Micromechanics, Magnet, Wireless operation, Biotechnology, In-pipe.**

I. INTRODUCTION

Intracavity intervention is expected to become an increasingly popular medical practice, both for diagnosis and in surgery. Several kinds of microrobots have been developed for various purposes owing to advances in precise process technology, and further progress in this field is expected. One use of a microrobot is as a tool in very small spaces, and in medical practice, their use avoids the need for dismantling and reassembling. In medical and industrial applications, a new type of microrobot in a pipe has urgently been needed [1]–[3]. The microrobot is installed with sensing and actuating elements, and can move smoothly in water or aqueous medium, making it suitable for pipe inspection and microsurgery of blood vessels.

A direct conversion of chemical activity to mechanical activity has been pursued by many researchers in order to achieve high efficiencies. Among various forms of locomotion, the forward swimming motion of a fish in water has been the subject of interest for zoologists, marine biologists, and engineers. Advantages of the wavy motion of the swimming body as compared to a mechanical propeller used in artificial swimming structures are numerous and can be attributed to its high energy-conversion efficiency, noiseless propulsion, and utilization of the energy of the surrounding medium. Mechanical swimming structures such as those replicating undulatory motion by means of linkages and other interfacing parts face the same problems as propellers, which have low efficiencies and excessive thermal energy generation. Recently, several types of microrobots in pipes using SMA, PZT, and polymer actuators have been reported [4]–[10]. However, some problems exist, such as compactness, low response, and safety in water.

II. STRUCTURE OF THE MICROROBOT IN PIPE

In this paper, a novel type of microrobot in a pipe which is presented that has flexibility, wireless control, good response, and safe application in the body. Up to now, several kinds of microrobots in pipe have been developed [4]–[10]. However, the power supply and the friction power with the inner wall were typically problematic in this research. It has been reported that a novel prototype model of a microrobot utilizing an electromagnetic actuator as the servo actuator to realize motion [11]–[12]. A moving fin driven by a permanent magnet can be controlled via frequency adjustment of the alternate magnetic field. Here an improved novel prototype model of a microrobot is proposed. Experiments were carried out, and operating characteristics were evaluated both in the horizontal direction and in the vertical direction. The proposed microrobot can correspond to the dirt adhering to the inner wall; it is capable of long-distance movement, even in vertical directions, and its speed can be easily controlled via frequency adjustment of the alternate magnetic field.

In **Fig.1**, shows the structure of a fin-driven type of microrobot. This microrobot is composed of a streamlined main body made of wooden and styrol materials; the fin consists of a polyimide film sheet, a permanent magnet which be shown in **Table 1.**

When current flows through a coil, an alternate magnetic field parallel to the promotion advance direction is applied;

this movement exerts force arising from a permanent magnet, which rotates and vibrates, and causes rotation and vibration of the fin connected to it. As a feature of the proposal, the structure is easy and it is possible to make it move by wireless. This research is carried out to taking up this proposal firstly. The prototype of the developed microrobot is shown in **Fig.2.**

TABLE 1 THE PARAMETER OF THE MAGNET

Size	Magnetic Field(B)	Weight	Magnetism
$\phi 4\times 2mm$	$330mT$	$0.19g$	$0.35kg$

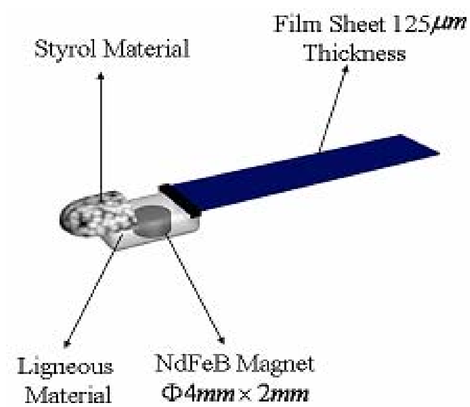


Fig.1. Structure of the Fish-like Microrobot

Fig.2. The Prototype of the Microrobot

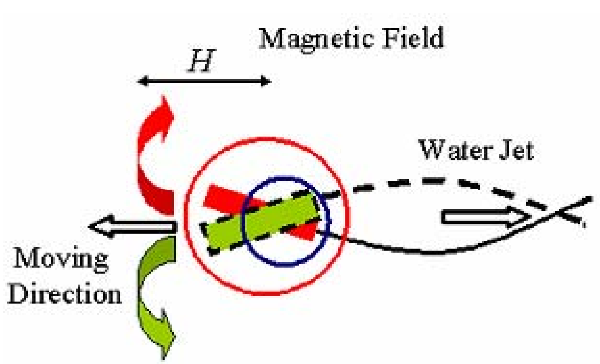


Fig.3. Driving Mechanism of the Microrobot

III. THE MOTION MECHANISM OF ROBOT

A. Kinematics of Driving Fin

According to biomechanics theory, a large undulatory motion near a fishtail results from an anguilliform mode of swimming, which involves most of the fish's body in an undulating or wavy motion.

Rosen [9] was among the first to explain the kinematics of motion in a simple carangiform fish through his observations using simple hydrodynamic forces and phenomena. He described the creation and evolution of vortices generated by the anterior half of the body (head and after-head of the fish) and cited them as the main reason for its propulsion through water. The fish further uses these vortices created by the last two-thirds 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 known as the "vortex peg hypothesis." The fish produces no net backward moving stream of water when swimming at constant speed. Only when the fish accelerates or turns around, is a trailing current created. The trail created by the fish is a system of large, slow-spiraling vortices. The trail consists of a single row of vortices with direction of rotation alternating from one vortex to the next. This row follows the path of the fish's head. The concave side of each flexural wave of the body of the fish contains one vortex. All main vortices are in line with and follow the fish's direction of travel. For a scaled fish, the mechanism of propulsion is even more complex since the convex portion of the body in effect has open scales that act as small paddles on the side of the fish, further pushing against the vortices to propel the fish forward. According to this theory on hydromechanics, a new novel structure of the fish-like microrobot has been proposed. Also we will discussed the motion mechanism, and characteristic evaluation of a driving fin used for propulsion.

B. Motion Mechanism

The microrobot has a fin driven by an alternate magnetic field; the fin is fixed on a permanent magnet. When current flows through the solenoid, a magnetic field is generated. when an alternate magnetic field parallel to the direction of advance is applied, movement due to an impelling force arising from a permanent magnet rotates and vibrates the connected fin as shown in **Fig. 3**. The propulsive force is the sum of the drag force vectors in the direction of movement as in **equation (1)**. The speed of the microrobot can be controlled by adjusting the frequency of the input current:

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

Where C_d drag coefficient is based on wetted surface area A ; ρ is the density of the fluid.

IV. CHARACTERISTIC EVALUATION OF FIN

A. Measurement System of the Driving Fin

A computer can control the electric current in the long solenoid coil, and the electrical current is measured by a galvanometer. The bending displacement of a fin at the front end is measured by a laser displacement sensor. The bending amplitude of the fin can be obtained; the measurement system is shown in **Fig.4**.

B. Characteristic Evaluation of a Driving Fin

Using the measurement system shown in **Fig. 4**, the following characteristics of a fin are measured. First, measure the maximum displacement of a fin at the front end by changing the frequency of current from 5 Hz to 60 Hz. **Fig. 5** shows the experimental results of the driving fins by frequency of input current. The experiment has been carried out at different conditions on the thickness and length of the fin. Here, the experiment is carried out as the length of fin is 2.5 centimeter. Maximum displacement is obtained when the frequency is 30 Hz and the current is 0.7A. According to selected experimental results, the natural frequency of the driving fin can be obtained. Characteristics of the driving fin using a cantilever model can be evaluated. The movement equation of horizontal vibration of a cantilever beam can be obtained from **equation (2)**:

$$EI\frac{\partial^4\omega}{\partial\chi^4}+\rho A\frac{\partial^2\omega}{\partial t^2}=0 \qquad (2)$$

If the conditions of fixed-freedom are substituted for the general solution of **equation (2)**, **equation (3)** can be obtained:

$$1+\cos\alpha\cdot\cosh\alpha=0 \qquad (3)$$

In this formula, α is the characteristic value. Using **equation (4)**, the natural frequency of a driving fin can be calculated as

$$f_i=\frac{\alpha_i}{2\pi}\cdot\frac{1}{l^2}\cdot\sqrt{\frac{EI}{\rho A}} \qquad (4)$$

where f_i is the natural frequency of the driving fin, E is the Young's modulus of the fin, I is the secondary section moment, ρ is the density of the fin, A is the cross-sectional area, l is the length of the fin, and α_i is the characteristic value of the fin.

V. CONTROL SYSTEM AND EXPERIMENT

A. The Position Measurement System

In this paper, it is proposed a method of measuring the position of the robot in pipe. On my research, the alternate magnetic field is applied by alternate current, in order to carry out this experiment; we use the DA board to obtain the alterable frequency and different wave form. On the basis of the DA board which can apply electrical signals, AD board is also used to receive external signals in order to measure the position.

In the position measurement system, firstly, the Hall Elements is used as induction element which is shown in **Fig.6 (a)**, and then, in **Fig.6 (b)** the electrical circuit should be developed into magnetic sensor. We set up two magnetic sensors onto the pipe in a short distance as shown in **Fig.7**. Therefore, when the robot moves between two sensors, the sensor will output the voltages separately. We can read the data on computer through the AD board, and remainder of two voltages can be obtained, thus, we can get a relation between the remainder and distance as a graph which is shown in **Fig.8**. And then, in **Fig.9**, it shows that how to calculate the coordinate of the robot. Firstly, the curve of the pipe should be assumed, here, it has been assumed as a half circle, so we can obtain an equation (5). Secondly, pick up the two points of optional position on the orbit of the microrobot, which the coordinate is defined (x_1,y_1), (x_2,y_2) and then utilize the distance formula, we can get the function (6). Lastly, According to the graph, we can get the approximate curve and calculate the equation (7), where ΔV is the voltage difference between (x_1,y_1) and (x_2,y_2), calculate (5), (6) and (7), equation (8) can be obtained. So according to (8), if we know the remainder of the voltages, we can know the position of the robot.

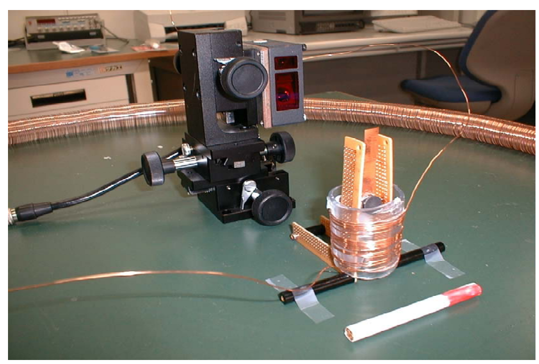


Fig.4. Measurement System for a Driving Fin

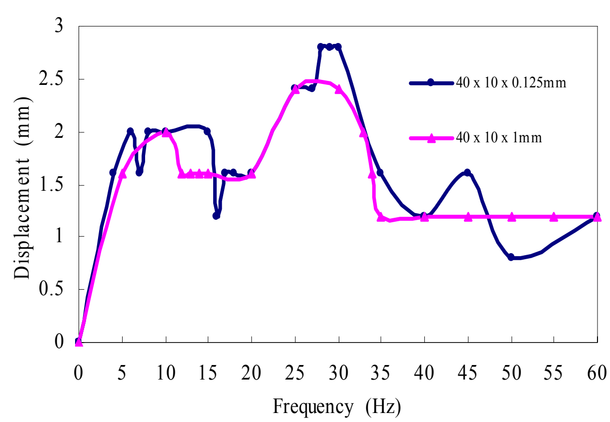


Fig.5. Displacement of Fin with Frequency

B. Moving State in Pipe

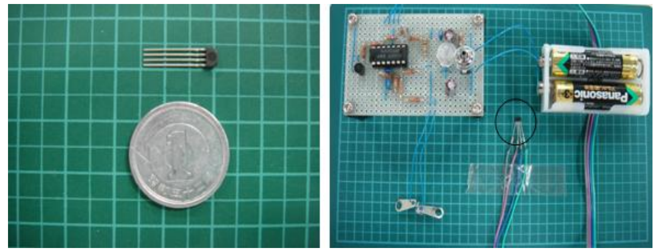
1) Moving Forward in Horizon: To evaluate the motion of microrobot in this paper, first we should carry out the experiment in horizontal direction. According to the experiment, we found that the fish-like microrobot can move steadily and safely, and also we carry out the experiment at the bifurcation point like as branch point. Here, we set up three channels on the coil, and we can control the robot by changing to the different channels. The state of moving in the pipe in horizon is shown in **Fig.10.**

2) Driving Upward by Fin in Pipe: The prototypes of developed microrobot have been shown in **Fig.2**. The permanent magnet is built in a main part. Also when we design and make the microrobot, we must consider the relation between flotage and deadweight. So it can suspend in water without outside force. In order to drive the microrobot by the alternate magnetic field with a coil, direction of magnetization of a permanent magnet is the height direction of a pillar. And then, for verifying the performances of the microrobot, we carry out the running experiments within a pipe of 1000mm height currently filled with water. It is considered that proposed moving mechanism is very effective. The state of driving upward of the microrobot is shown in **Fig.11 (a)**.

3) Analysis of the State of Stopping in Pipe: Many researches on underwater microrobot or fish-like microrobot in pipe have been done well recently. Even much work has been done in area of matching propulsion requirements to the optimal propeller. However, some of them have ignored the characteristic on discretionally stopping; especially it can stop in vertical direction without wire. If the developed microrobot can be used widely in biological and chemistry field, we must focus on the point of "stopping".

In this paper, a method of stopping has been introduced completely. The magnetic robot can move upward and downward freely by changing the frequency. On the other hand, according to the theory of the motion, in order to obtain alternation magnetic field, an alternating current is required. And then permanent magnet carries out rotation vibration.

In **Fig.11 (b)**, shows when we want it to stop vibrating and repose anywhere, we can change the alternating current into direct current. There will be a parallel magnetic field which is in the same direction in solenoid at once. The magnet will have a turning trend to parallel direction caused by the magnetic torque, M shown in **Fig.12**. Because of the torque, a pair of force F is vertical to the head. As a component of the force, the pressure F_N is vertical to the inner wall. So the biggest static friction of the head, $f_{\max}$ equals to $2F_N f$, where f is the coefficient of the friction, shown in equation (9) to (12). When the resistance, from the weight or fluid, is less than $f_{\max}$, the robot can stop depending on the friction of the inner wall.



(a) Hall Elements (b) Electric Circuit

Fig. 6. Magnetic Sensor System

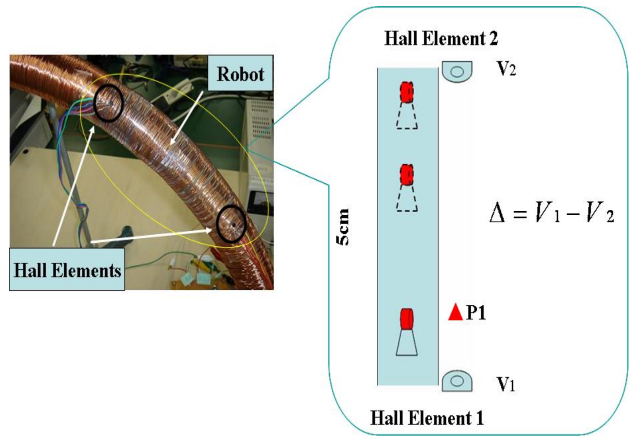


Fig.7. Measurement System for Position of the Robot

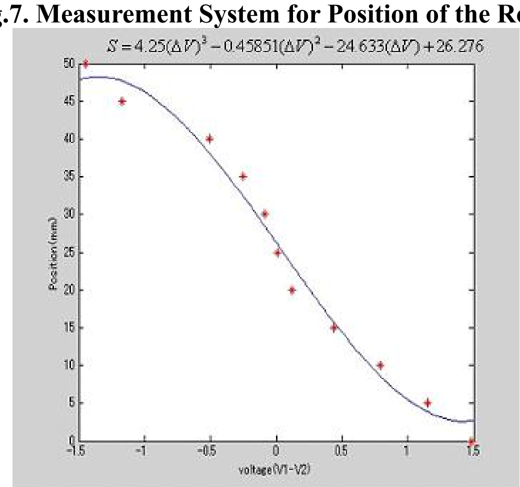


Fig.8. Experimental Result of the Position with Voltage

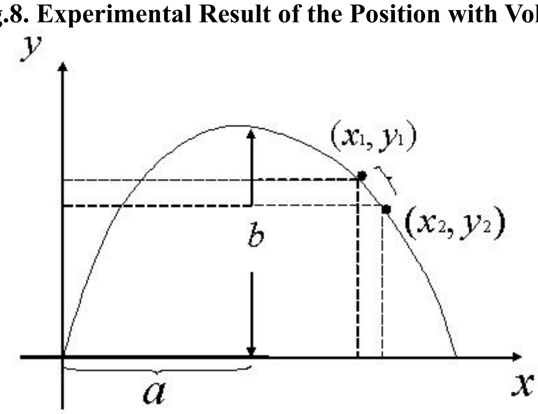


Fig.9. Position Calculation

$$(x-a)^2 + y^2 = b^2 \tag{5}$$

$$S = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{6}$$

$$S = 4.25(\Delta V)^3 - 0.45851(\Delta V)^2 - 24.633(\Delta V) + 26.276 \tag{7}$$

$$x = x(\Delta V) \tag{8}$$

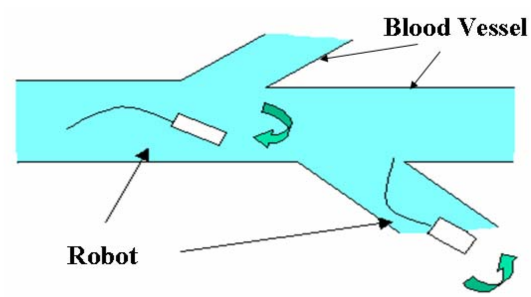
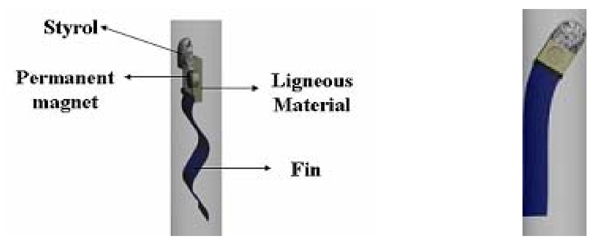


Fig.10. Microrobot Moving in Horizontal Pipe



(a) Going up (b) Stopping

Fig.11. Microrobot Moving in the Vertical Pipe

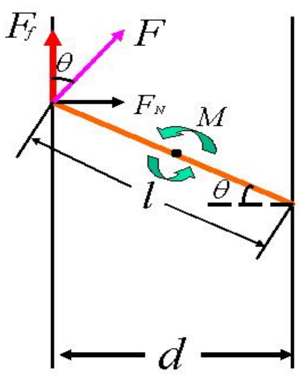


Fig.12. Stopping Model in the Vertical Pipe

$$M = Fl \tag{9}$$

$$F_N = F\sin\theta \tag{10}$$

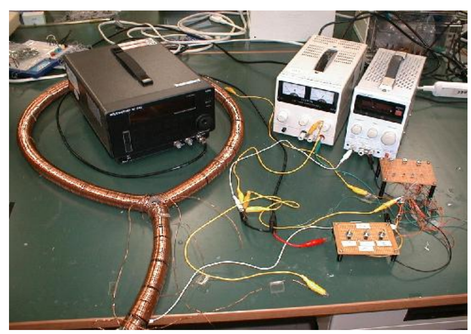
$$\theta = \arccos\frac{d}{l} \tag{11}$$

$$F_{f_{\max}} = 2F_N f = 2\frac{Mf\sqrt{l^2 - d^2}}{l^2} \tag{12}$$

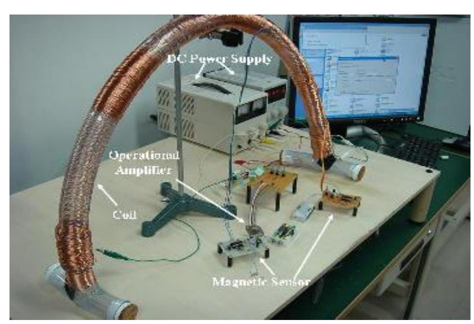
VI. EXPERIMENTAL RESULTS

We made the running experiments of the prototype microrobot using a measurement system. We measured the running speed for various frequencies on different conditions using a high-speed camera as shown in **Fig.13.** By changing the frequency from 0Hz to 80Hz, the experimental results of average horizontal moving speed are obtained as shown in **Fig14**, and by changing the frequency from 0Hz to 5Hz, the vertical moving speed has been obtained as shown in **Fig15.** According to the experimental results, we can find that the thickness of the tail of the robot have an influence on speed of the robot. And we also can find that the maximum speed can be obtained at 20Hz in horizontal direction, at 2.5Hz in vertical direction. Specially, in vertical direction, when the frequency is more than 3.8Hz, the speed of the tail of the thicker one is faster than the thinner one, because when increasing the frequency, the motion state of the tail of the thicker one has changed to oscillation, the propulsive force will be occurred.

However, the measurement of the displacement of the fin has been introduced at the front page in this paper, the maximum displacement which can be obtained in the air when the frequency is about 30Hz, but here the maximum speed that has been obtained in the water as the frequency is 20Hz. It means that the fluid has an influence on the fin of the microrobot. So some decisive factors like as viscosity and fluid density must be considered in the following research.



(a) Experiment in Horizontal Direction



(b) Experiment in Vertical Direction

Fig.13. Measurement System of the Running Speed

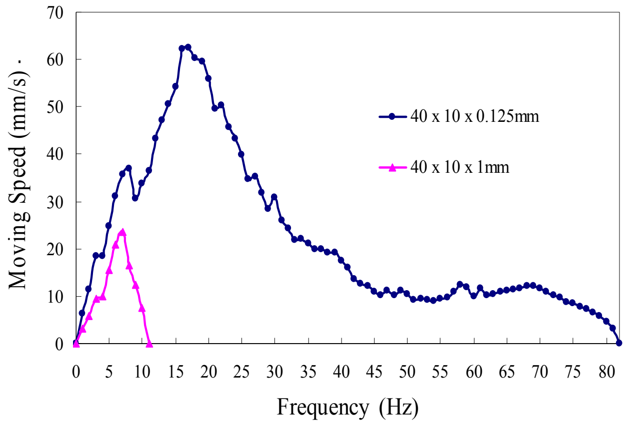


Fig.14. Experimental Result of the Speed in Horizon

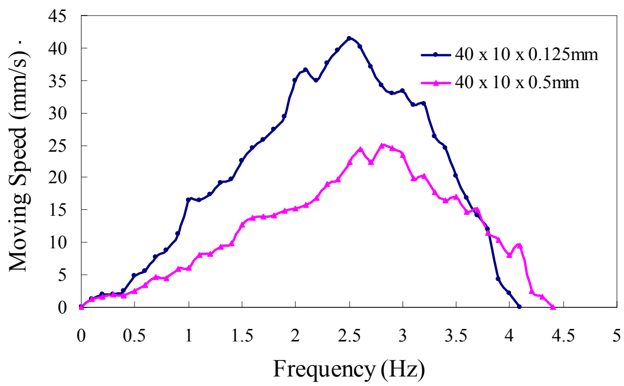


Fig.15. Experimental Result of the Speed in Verticality

VII. CONCLUSION

A novel type of microrobot in a pipe has been proposed using an alternate magnetic field and discussed the structure, motion mechanism, and evaluation of a driving fin. The running speed of the microrobot was measured in the horizontal and vertical directions by changing the frequency of the input current from 0 to 80 Hz. The experimental results showed that maximum running speeds of 65 mm/s and 40 mm/s could be obtained in the horizontal and vertical directions, respectively. Furthermore, these frequencies approximate natural frequencies must be noted.

Moreover, in this paper, a method of the measurement of the position has been introduced completely, and through utilizing this method, we have carried out the experiment to prove that it is feasible. Therefore, we can carry out the experiment in sightless or invisibility environment very well. In other words, it is useful for some research on self-walking robot at biomedical field.

In the future, the design and energy supply of the wireless microrobot will be optimized. Design and use an electromagnetism sensor for detecting the location of the microrobot in a pipe and for accurately controlling its speed and position must be realized. This device will play an important role in industrial and medical applications, for example, to conduct in-pipe inspections. It also possesses a high potential for use in the microsurgery of blood vessels and in minimally invasive medical procedures.

REFERENCE

[1] Barrett D, Yue D.K.P, Grosenbaugh, and Wolfgang M.J, “Drag reduction in fish-like locomotion,” Journal of Fluid Mechanics 392, pp.183-212, 1999.

[2] Laurent G, Piat E, “Efficiency of Swimming Microrobots using Ionic Polymer Metal Composite Actuators,” IEEE International Conference on Robotics & Automation, pp. 3914-3919, 2001.

[3] Gray J, “Studies in Animal Locomotion, VI. The PropulsivePowers of the Dolphin”, J. Exp. Biol. 13, pp.192-199, 1936.

[4] Anderson J.M, Triantafyllou M.S, Kerrebrock P.A, “Concept design of a flexible-hull unmanned undersea vehicle,” Proceedings of the International Offshore and Polar Engineering Conference, pp.82-88, 1997.

[5] Harper K.A, Berkemeier M.D, and Grace S, “Modeling the dynamics of spring-driven oscillating-foil propulsion,” IEEE Journal of Oceanic Engineering 23, pp.285-296, 1998.

[6] Oguro K, Asaka K, and Takenaka H, “Polymer film actuator driven by a low voltage,” in Proc. of 4th International Symposium on Micro Machine and Human Science, pp. 39-40, JAPAN, 1993.

[7] Fearing L, “Micro structures and micro actuator for implementing submillimetres robots,” Precision Sensors, Actuators and Systems (Kluwer Academic Publishers), pp.39-72, 1992.

[8] Mojarrad M, and Shahinpoor M, “Biomimetic robot propulsion using polymeric artificial muscles,” in Proc. of 1997 IEEE International Conf. on Robotics and Automation, New Mexico, USA, pp.2152-2157, 1997.

[9] Sendoh M, Yamazaki A, Ishiyama K, “Wireless controlling of the swimming direction of the spiral-type magnetic micro-machinrs,” Trans. IEEE Japan, Vol.120-A, pp.301-306, 2000.

[10] Guo S, Sasaki Y, Fukuda T, “A fin type of microrobot in pipe,” Proc. of the 2002 International Symposium on Micro Machine and Human Science (MHS' 22), Nagoya, pp.93-98, 2002

[11] Guo S, Sasaki Y, Fukuda T, “A New Kind of Microrobot in Pipe Using Driving Fin,” IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM 2003), Kobe, Japan, pp.667-702, 2003.

[12] Domenici P and Blake R. W, “The kinematics and performance of fish fast-start swimming”, The Journal of Experimental Biology, pp.1165-1178, 1997.

[13] Guo S, Pan Q, Khamesee M.B., “Development of a Novel Type of Microrobot for Biomedical Application”, ASME/JSME joint conf. (MIPE 2006), Santa Clara, CA, USA, June 2006.

[14] Guo S, Fukuda T, Asaka K, “A new type of fish-like underwater microrobot”, IEEE/ASME Transactions on Mechatronics, Vol.8, No.1, pp.35-40, 2003.

[15] Guo S, Sakamoto Jun and Pan Qinxue, “A Novel Type of Microrobot for Biomedical Application,” 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2005), Canada, pp.2265-2270, 2005.