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Development of a Wireless Hybrid Microrobot for Biomedical Applications

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Abstract – **In this paper, to deal with the locomotion and performance in pipe or even in blood vessel condition, we design a novel type of hybrid microrobot that has characteristics of multi-functions, controllability, stability. The hybrid microrobot has simple structure, simple control method, and good dynamic. We develop the microrobot composed of rotating motion and fish-like locomotion to realize the wireless controllability capable of swimming and rotating motion. We design the rotation magnetic field, the motion mechanism of rotating motion and fish-like motions have been analyzed as well. Also, we design the hybrid microrobot by combining the rotating motion and fish-like fin motion. By applying the rotation magnetic field, we carried out the evaluating experiments for rotating motion and moving motion in a pipe. The experimental results indicated that, for the rotating motion, the rotating speed of 87rad/s and moving speed of 58mm/s; for the hybrid microrobot, the moving speed of 48mm/s can be obtained via frequency of the input current. Additionally, it is demonstrated that the microrobot has a rapid response. This microrobot will play an important role in both industrial and medical applications such as microsurgery.**

I. Introduction

Microsurgery in blood vessels is expected to become an increasingly popular medical practice. As wireless microrobots controlled by a magnetic field are both safe and reliable, and can be carried deep within the tissues of living organisms in the body fluids, they have many potential applications in the field of medical engineering. For example, they may be used for microsurgery in blood vessels, which is expected to become an increasingly widely adopted medical procedure in the near future. With advances in precision processing technology, several types of microrobots have been developed for various applications and further progress in this field is expected.

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In recent, magnetic actuation technology has been applied in biological systems for many years when wireless actuation is needed. A common application area is targeted drug delivery where magnetized carrier particles that are coated with various chemical agents are concentrated on specific target region of the body using external magnetic fields. A biomedical microrobot with a Hybrid MEMS [3] design is being developed with the first area of application of this robot will be ophthalmic operations on the retina. It is an early prototype micororbot with a three dimensional structure that was built to investigate hybrid MEMS assembly and magnetic steering concepts.

Until now, there are several kinds of microrobots utilizing the magnetic actuators. Magnetic actuator for use in colon endoscope [8] composed of tube-shape permanent magnet and spiral structure made by rubber. By applying the rotation magnetic field, the actuator with flexible air tubes can move in small and large intestines of pig. Also, several types of swimming microrobot [1][6], are developed using an ICPF actuator and cable, which can move forward, float up and down. A remarkable biomedical swimming robot [9] has been developed inspired by the motility mechanism of prokaryotic microorganisms, the flagellar propulsive force can be obtained 25mN. Especially, wireless microrobots also have been developed well. Honda [10] developed a new kind of wireless swimming robot with tail fin which can swim in one direction. Thereafter Mei Tao [11] developed another kind of wireless drive micro swimming robot with desirable experiment results by using a new kind of intelligent magnetic material FMP. And also Guo et al [4][5][7] developed a novel type of wireless swimming robot that can move not only in horizontal direction but also vertical direction, especially it can turn right and left by controlling the external magnetic field.

In a word, biomimetic underwater swimming microrobots are of great interest for exploring unstructured underwater environments and for microsurgery within blood vessels for minimally invasive medicine. Furthermore, the requirement of a wireless energy supply for underwater microrobots has been addressed for practical applications.

This paper focuses on the development of a wireless hybrid microrobot capable of moving and rotating motion, high thrust using magnetic actuators.

In this paper, firstly, we propose the structure and the prototype of the hybrid microrobot. Secondly, we analyze mechanism of each motion and evaluate the rotating motion and fish-like locomotion. Thirdly, we design the control system and carry out the experiment of the moving speed. The last is our conclusions.

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II. Structure Of The Hybrid Microrobot

In this paper, a novel type of hybrid microrobot in a pipe which is presented that has wireless control, good response, and safe application in the body. Up to now, several kinds of microrobots in pipe have been developed [4] – [11]. Especially, by applying the rotational magnetic field, a kind of rotate machine which can move in an intestine has been developed by Sendoh [8]. This kind of microrobot can move forward by the propulsive force from the inner wall while rotating. In this paper, we introduced the microrobot which can be propelled by low voltage, and has a quick response.

And also, for the advantage of this kind design of the microrobot, it can not move smoothly in the human body but also it can remove the obstructing in intestine or blood vessel using the particular structure.

The proposed hybrid microrobot consists of rotating motion and fish-like locomotion. The front of the microrobot is like as a drill bit. As the name suggests, it can obtain the propulsive force while the body rotating at low frequency, and even through there are some impediment in the pipe, intestine and blood vessel, it can destroy the obstructions and continue to move forward as well. The fish-like locomotion also can generate a propulsive force at high frequency. Therefore, we can realize the control of the robot in wide range of frequency. This function or technique is the important for biomedical application, it also can be used in diseases thrombus and aneurism.

Based on the magnetic theory, in order to rotate the microrobot in the magnetic field, we should create at least a pair of force with opposite direction; in the meantime, the rotating moment should be generated as well. According to this two factors above, we set four permanent magnets in the top, bottom, front and back of the body, respectively, they are not in the same line in order to generate rotating motion. And also, the fish-like fin is set on the back of the rotation part. A permanent magnet which be shown in Table I. The structure of the proposed hybrid microrobot is shown in Fig. 1. The prototype microrobot is shown in Fig. 2.

TABLE I
THE PARAMETER OF THE MAGNET

Size	Magnetic Field(B)	Weight	Magnetism
$\phi 4\times 4mm$	$430mT$	$0.37g$	$0.52kg$

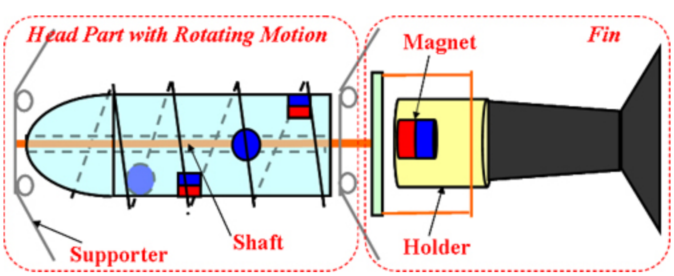


Fig. 1. Structure of hybrid microrobot

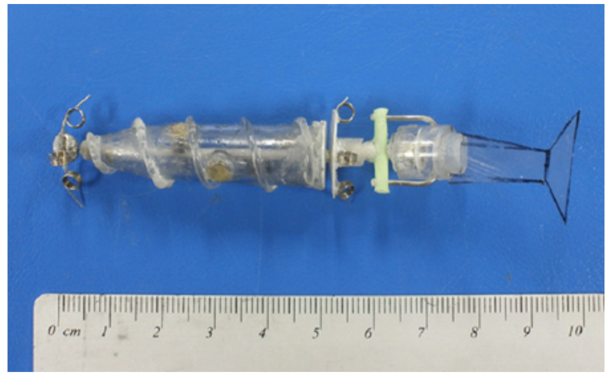


Fig.2. The prototype of the hybrid microrobot

III. Design Of The Rotation Magnetic Field

A. Review of the Previous Study on Magnetic Field

As we know, in a coil, a large field is produced parallel to the axis of the coil as shown in Fig. 3. Components of the magnetic field in other directions are cancelled by opposing fields from neighbouring coils. Outside the solenoid, the field is also very weak due to this cancellation effect and for a solenoid which is long in comparison to its diameter, the field is very close to zero. Inside the solenoid the fields from individual coils add together to form a very strong field along the center of the solenoid.

To calculate the magnitude of the field in the solenoid, we used the Ampere's law as shown in equation (1). Ampere's law relates the circulation of B around a closed loop to the current flux through the loop.

$$\oint_L \vec{B}\cdot d\vec{l} = \oint_L B\cos\theta dl = \oint_L \frac{\mu_0 I}{2\pi r} r d\varphi = \frac{\mu_0 I}{2\pi}\int_0^{2\pi} d\varphi = \mu_0 I \quad (1)$$

By using the ampere's law, we can calculate the magnetic flux for the infinite solenoid as shown in Fig. 4.

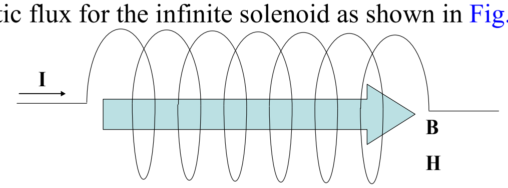


Fig. 3. Magnetic field in coil

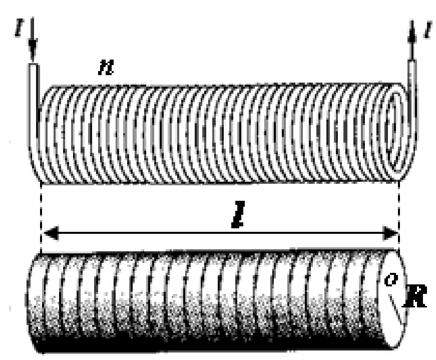


Fig. 4. Concept of solenoid

For the infinite solenoid shown as Fig. 4, we assume the distance between the turns to be 0, and then, calculate the magnetic flux density of P where is on the axis of the solenoid as shown in equation (2).

$$B_p = \frac{\mu_0 n I}{2}\left[\frac{x_2}{\sqrt{x_2^2+R^2}} - \frac{x_1}{\sqrt{x_1^2+R^2}}\right] \quad (2)$$

Where, x_1 is the distance to one side of the solenoid; x_2 is the distance to the other side of the solenoid. So, if x_1 is to be $-\infty$, and x_2 is to be $+\infty$, we can obtain the magnetic flux on the axis of the solenoid as shown in equation (3).

$$B = \mu_0 n I \quad (3)$$

where, B is the magnetic flux density; H is the magnetic field strength; μ_0 is the permeability of vacuum; n is number of turns in unit length; I is the current in coil.

And the magnetic torque T acting on the permanent magnet in the external magnetic field H is given by:

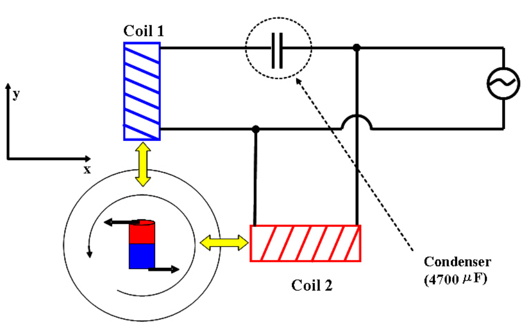
$$T = M \times H \quad (4)$$

Where, M is the magnetic moment of the permanent magnet.

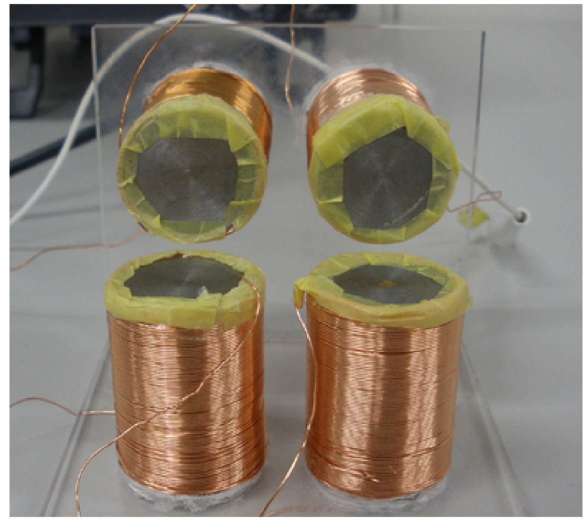
B. Design of the Rotation Magnetic Field

In our previous studies, we simply drove the microrobot using an alternating magnetic field in only the horizontal direction. Due to the structural design limitations of the microrobot, we designed a new external superposition magnetic field with horizontal and vertical directions as shown in Fig. 5(a). Therefore, we set the coil 1 and coil 2 at 90 degrees to each other. And also, in order to control the robot stably, we need a constant magnetic field in a distance, so we set two pairs of the coils as shown in Fig. 5(b). We used the condenser $4700\mu F$, so as to generate the phase difference of 90 degree as shown in Fig. 6. The single phase alternate current will be set to flow in the coil 1 and coil 2. It is a simple design to obtain the rotation magnetic field.

In order to generate the rotation magnetic field, we made the solenoid by using enamelled wire. Especially, we inserted the magnetic core SS400 to enhance the magnetic flux density. Then, by utilizing gauss meter, the relationship between the magnetic flux density H and current I can be obtained as shown in Fig. 7, and the equation (5) can be obtained as well.



(a) Driving circuit



(b) Two pairs of the coils

Fig. 5. Rotation magnetic field

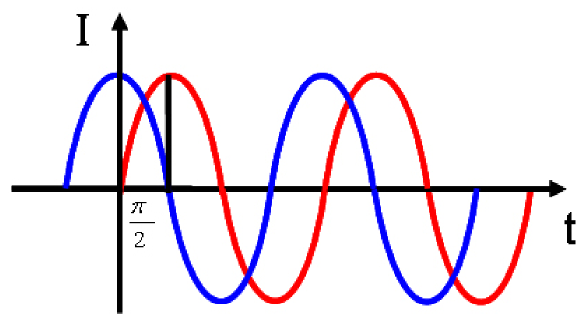


Fig. 6. The signals in rotation magnetic field

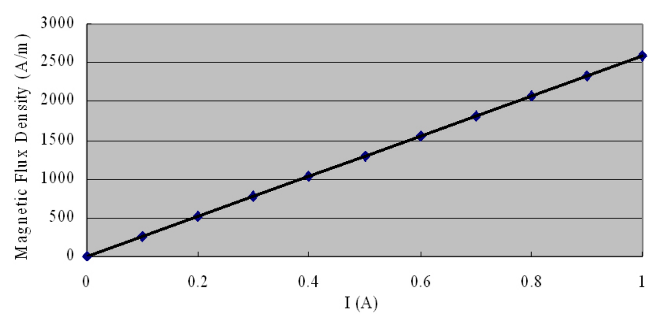


Fig. 7. Relationship between magnetic flux density and current

$$H(i) = 2.583\times10^3 \times i \quad (5)$$

IV. Motion Mechanism of the Hybrid Microrobot

A. Motion Mechanism of the Head Part

Based on the rotation magnetic field mentioned above, we set four magnets embedded in the body shown in Fig. 8 (a), two on the front and two on the back. They are not aligned on the same line, so as to provide the rotating torque. Also, the polar of the two magnets are in the same direction, respectively. The cross-section of position of the magnets is shown in Fig. 8 (b).

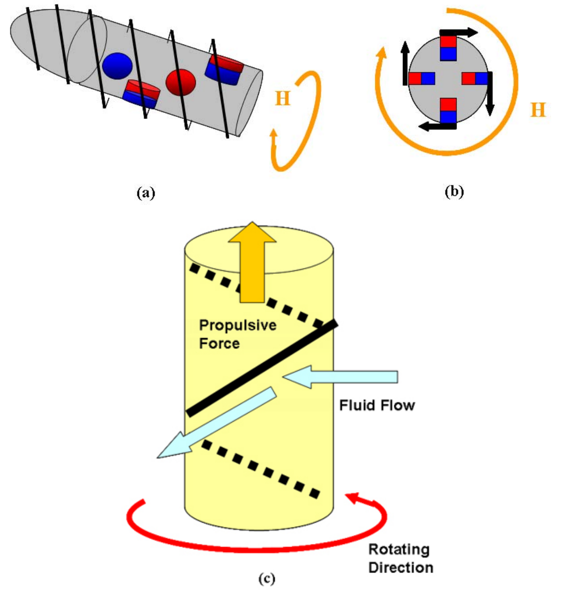


Fig. 8. Motion mechanism of the head part with rotating motion

B. Motion Mechanism of the Fin

As shown in Fig. 9(a), when current flows through a coil, an alternate magnetic field will be generated. Because of the torque of the magnet, the head of the robot will do the movement of the rotation vibration. And the fin is connected with the head, so it also starts doing the same movement with head. In this way, the propelling force can be generated, and the robot can move forward while adjusting the frequency of input current. As a feature of the proposal, the structure is easy and possible to make it move by wireless.

In this research, we will drive the hybrid microrobot using the rotation magnetic field. In order to realize the rotation vibration of the fin in Y direction, the structure will be made as shown in Fig. 9(b). The rotation magnetic field has been realized by superposition with X axis and Y axis mentioned above, therefore we fix a shaft through the holder, then, it only can rotate by Y axis.

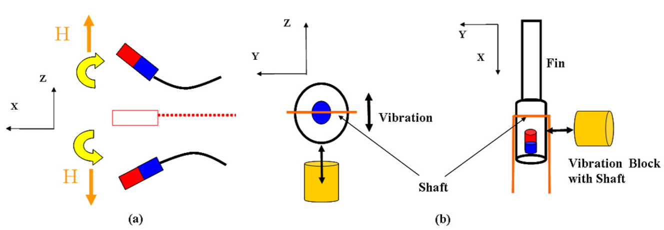


Fig. 9. Motion mechanism of the fin

C. Design of the Driving Fin

According to the motion mechanism of the fin, we developed the prototype of the fin shown in Fig. 10. In order to actuate the fin by external magnetic field, we set a magnet in the holder of the fin. The size of the fin is shown in Fig. 11. Also, we designed three kinds of the fin in different sizes and material as shown in Table II to carry out the evaluating experiments.

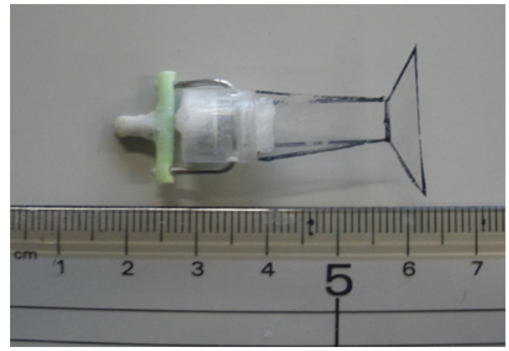


Fig. 10. The prototype of the fin

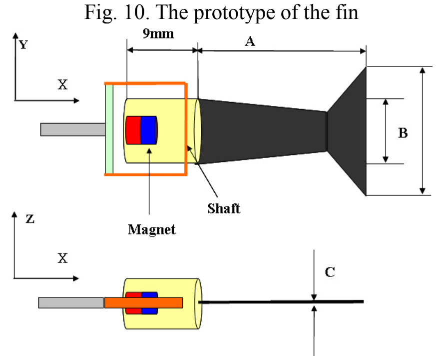


Fig. 11. Dimension of the fin

TABLE II

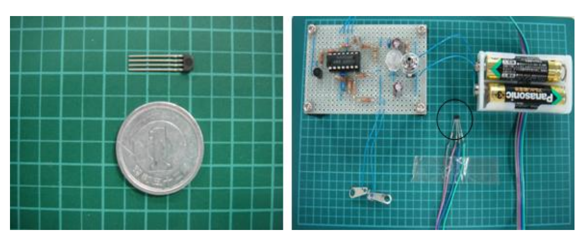
THE SIZE OF THE FIN (unit: mm)

	Length A	Width B	Thickness C	Material
Fin 1	30	10	0.1	Polyethylene
Fin 2	20	10	0.1	Polyethylene
Fin 3	30	10	0.2	Aluminum Board

V. CHARACTERISTIC EVALUATION OF HYBRID MICROROBOT

A. Measurement System of the Rotating Motion

In this measurement system, the main equipments are the coil and the amplifier circuit. So we use the two DC power supply to obtain the input current. We can control the speed of the spiral locomotion of the robot by adjusting the output signals from the functional generator. We use the hall element THS119 shown in Fig. 12 to develop the amplifier circuit. When the alternate current flows in the coil, the magnetic field is generated, the robot can rotate. In this way, by utilizing the hall element, we can read the numbers of turns through the PCI board. The measurement system for the rotation speed is shown in Fig.12.



(a) Hall Elements (b) Electric Circuit

Fig. 12. Magnetic sensor system

B. Characteristic Evaluation of the Rotating Motion

By using the measurement system shown in Fig.13, the following characteristics of the rotation speed are measured. We carry out this experiment by changing the frequency of input current from 0 Hz to 15 Hz. In order to measure the rotating speed, the Hall Element is used as induction element. We set up one magnetic sensor onto the pipe as shown in Fig.16. If the object rotates in the pipe, the magnetic sensor can be induced by the magnet. When the object rotates one cycle, we can monitor the peak of the sin wave will appear twice by using oscillograph. Therefore, applying the signals with different voltages and frequencies, we read the time from PCI board and the calculated rotating speeds are shown in Fig.14. It shows the experimental results of the rotation speed by frequency of input current. Maximum rotation speed is obtained when the frequency is around 10 Hz and the current is 0.7A.

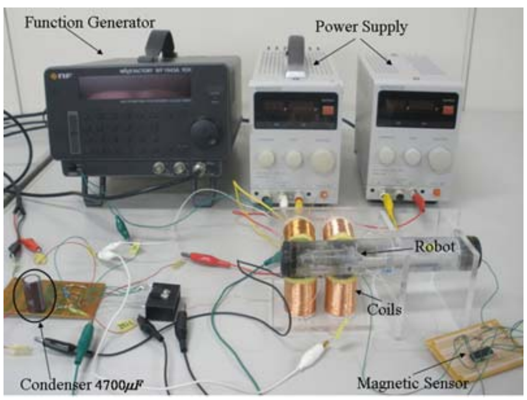


Fig.13. Measurement system of the spiral locomotion

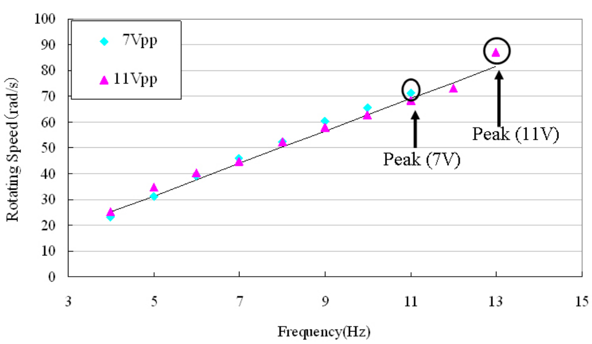


Fig.14. Experimental results of the rotating speed

C. Characteristic Evaluation of the Fin

A computer can control the electric current set onto the long solenoid coil. 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. Measurement system is shown in Fig. 15.

Also, based on the measurement of the fin, we carried out the movement experiment for the fin by using two kinds of the fin in different length. By adjusting the frequency from 0Hz to 100Hz of the input current, we can get the experimental result as shown in Fig. 16. Based on the result, the top speed for the fin of 25mm/s can be obtained in low frequency.

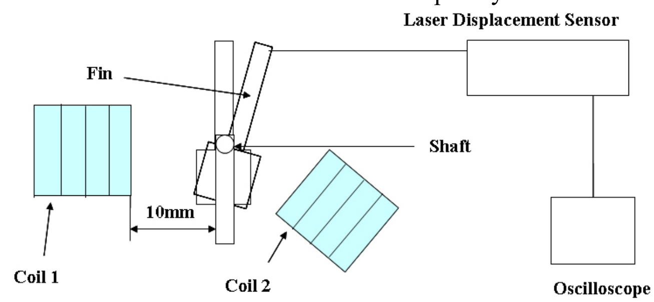


Fig. 15. The measurement system for the fin

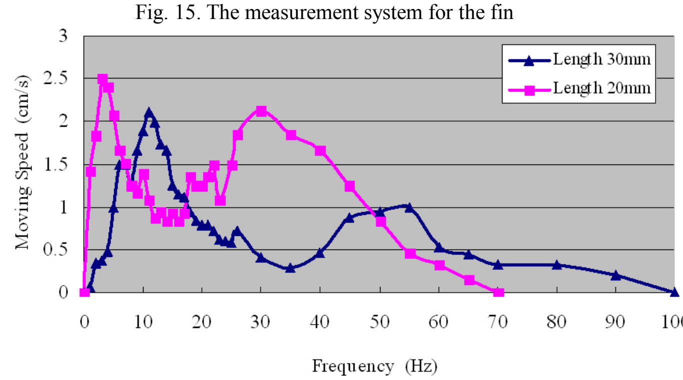


Fig. 16. Moving speed of the fin

VI. Experiment and Experimental Results

In order to amplitude the signals applied by the function generation, we use the operational amplifier with high output to setup the control system. By testing the proposed amplifier circuit, the signals can be amplified 2.3times of the amplification factor. And a photo of the developed control system has been illustrated in Fig. 17.

For the rotating motion, we carried out the experiments to measure the moving speed. As shown in Fig.13, we set up two pair of magnetic fields onto the pipe in a short distance, and then the object moved forward and backward, we recorded the time for moving motion, and the calculated motion as shown in Fig.18. The moving speed of the hybrid microrobot is shown in Fig. 19. The result indicates that when the frequency from 0Hz to 26Hz, the dynamic of the rotation is superior to the fin; when the frequency is in excess of 26Hz, the fin is superior to the rotation motion. Also, the moving speed of 48mm/s for the hybrid microrobot can be obtained.

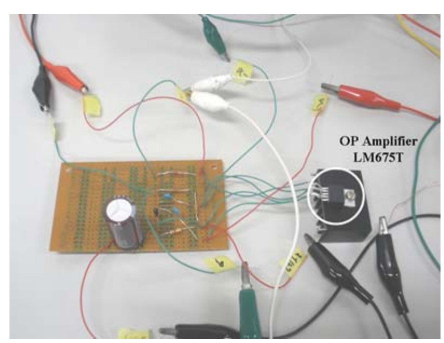


Fig. 17. Driving circuit of control system

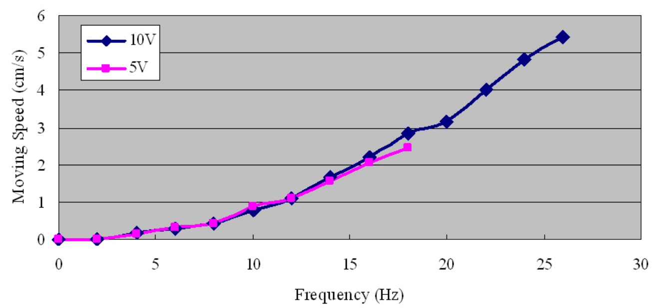


Fig. 18. Moving speed of head part with rotating motion

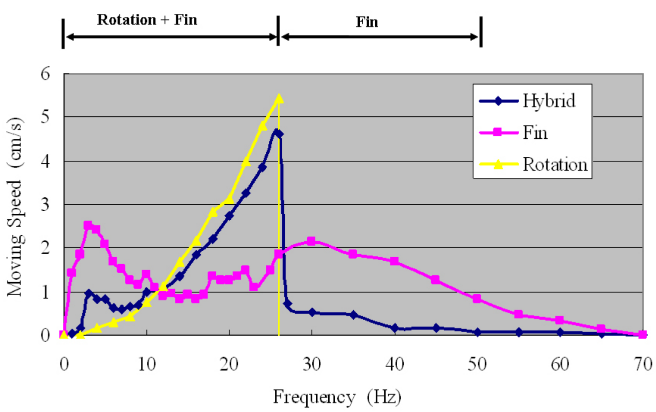


Fig. 19. The speed of moving motion with different voltage

VII. Conclusion

In this paper, to realize a kind of micro machine that can deal with the performance in pipe, intestine or blood vessel, a novel type of hybrid wireless microrobot in pipe has been proposed. We also discussed the structure, motion mechanism, and characteristic evaluation of a rotating motion and fish-like fin for the microrobot. Based on the previous study, especially we learned from the features of the magntic flux density in solenoid or coil. Then, we designed the external rotation magnetic field. We analyzed the mechanism of rotating motion; also, we designed a fin that how it can be controlled in rotation magnetic field. Thirdly, we evaluated the characteristic of rotating motion and fin, carried out the experiment for the rotating speed, the experimental result indicated that the top rotating speed can be obtained 87 rad/s, it demonstrated the rotating motion has been realized. Then, the characteristic of the fin has been evaluated as well. The amplifier circuit and control system also have been set up, and carried out the experiment to measure the moving speed for the hybrid microrobot. The experimental results indicated the top moving speed of 48 mm/s can be obtained.

In the future, the design and energy supply of the wireless microrobot will be optimized further. This kind of spiral type wireless microrobot will be useful in industrial and medical applications.

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