Proceedings of 2013 ICME
International Conference on Complex Medical Engineering
May 25 - 28, Beijing, China

Development of a New Kind of Magnetic Field Model for Wireless Microrobots

Jian Guo[*1], Shuxiang Guo[*1,*2]
*1 School of Electrical Engineering
Tianjin University of Technology
Tianjin, China
gj15102231710@163.com

Xiang Wei[*1], Wei Wei[*1] and Yunliang Wang[*1]
*2 Intelligent Mechanical Systems Engineering Department
Kagawa University
Takamatsu, Kagawa, Japan
guoshuxiang@hotmail.com

***Abstract* – In the industrial field and medical application, a wireless microrobot may be used in the small space and medical practice. In this paper, we proposed a new kind of magnetic field model, which can generate a rotation magnetic field directly and drive a microrobot. In addition, we proposed a spiral wireless microrobot, which can work in narrow area such as blood vessels in application to microsurgery. The developed microrobot with a spiral structure can get very strong force to move and has the characteristics such as compact volume, completely symmetrical mechanical structure, quick response, cleaning the dirt adhering to the inner wall, and long distance movement. We can just change the characteristic of input current to control movement of the microrobot easily. It can move smoothly in water or other liquid medium and we are able to achieve wireless, high efficiency energy supply. Then through the theoretical analysis and software simulation of the rotation magnetic field model, we verify the feasibility of the new model and the motion characteristics of microrobot. It will be very useful for industrial application and microsurgery.**

Index Terms* – *Wireless Microrobot, Magnetic Field Model, Spiral Structure, Medical Application.

I. INTRODUCTION

Endovascular intervention has become more and more popular in recently, and it is widely used in medical practice, diagnosis and surgery. Pipeline micro-robot is an important research branch of MEMS (Micro-Electro-Mechanical System). It consists of two aspects. One is to walk in the hard pipe, which is widely used in many fields of the chemical engineering, nuclear power plant and refrigeration. The other one is to walk in the flexible pipe, such as the human gastrointestinal (GI) tract, the blood vessel, for medical treatment. With the development of MEMS technology, make the micro-robot which is as a tool in very small spaces, and in medical practice, possible to enter the body and execute non-invasive or minimally invasive medical operations. In order to safely and reliably complete the intestinal examination and surgical operations, to reduce the suffering of the patients, 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. In medical and industrial applications, a new type of microrobot in a pipe has urgently been needed [1] - [3]. They can move smoothly in water or other liquid medium, making it suitable for pipe inspection and microsurgery of blood vessels. However, there are still some problems exist, such as compactness, low response, and safety in water.

Recently, magnetic actuation technology has been applied in biological systems for many years when wireless actuation is needed. Until now, there are several kinds of microrobots utilizing the magnetic actuators. Magnetic actuator for use in colon endoscope composed of tube-shape permanent magnet and spiral structure made by rubber [4]. Honda developed a new kind of wireless swimming robot with a tail fin which can swim in one direction [5]. Thereafter Mei Tao developed another kind of wireless microrobot with desirable experiment results by using a new kind of intelligent magnetic material FMP [6]. And especially Professor Guo et al 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 as in [7] - [12].

In our study, previous researchers have developed several kinds of alternating magnetic field driven models as shown in Fig. 1 [3][11][12] .

Fig.1 Three kinds of alternating magnetic field driven model

In the alternating magnetic field of the one-dimensional, the control strategies are very simple, but microrobot can only achieve move the fin motion just like a fish. We also can change the DC input to make microrobot directional movement. In the two-dimensional alternating magnetic field, the microrobot can achieve rotating motion and fish-like locomotion, but needs five pieces of permanent magnets in the mechanical structure. In the three-dimensional alternating magnetic field, the microrobot can achieve hybrid motions, such as rotating motion, paddling motion and fish-like locomotion. It has flexible movement forms, but it still with too many pieces of permanent magnets, so can't get a more compact mechanical structure in the present situation.

In the hybrid motions, the kind of spiral motion can not only obtain the maximum driving force, but also is the highest efficiency. So we proposed a microrobot with a symmetrical

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spiral structure immediately, and we also need a rotation magnetic field to drive it easily.

In this paper, we focus on the development of a new kind of rotation magnetic field model driven model at first, it will with the following properties:

1. A three-dimensional magnetic field, the robot posture can be realized as the change of three degrees of freedom.
2. Control easily (just change the current frequency and phase).
3. The microrobot can move forward and backward in theory
4. Rapid response.

And then we proposed a prototype of wireless microrobot with a compact spiral structure.

II. ANALYSIS OF ROTATION MAGNETIC FIELD MODEL

A. *Theory of a rotation magnetic field*

The fact of rotation magnetic field can be produced, either by rotating a permanent magnet or an electromagnet. It was realized that a rotation magnetic field could be produced by stationary poly-phase coils carrying polyphase currents by Nikola Tesla and others in 1885. If a three-phase symmetrical coil through symmetrical three-phase AC current, we can get a rotation magnetic field as shown in Fig. 2.

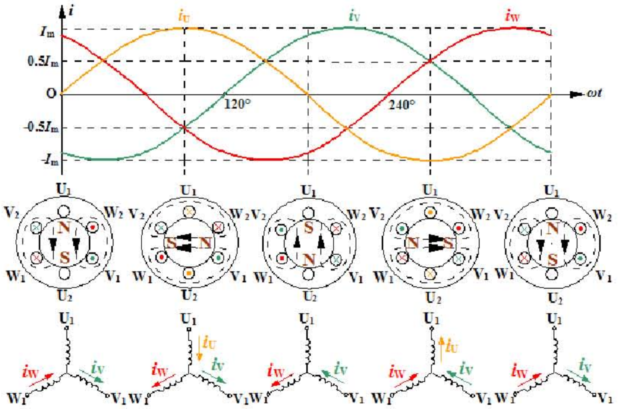


Fig.2 Establishment of the rotation magnetic field

In a circle, the times of ωt=0, π/2, π, 3π/2 etc, we can find four special positions of the magnetic field such as the times of ωt=0, π/2, π, 3π/2 etc, as shown in Fig. 3.

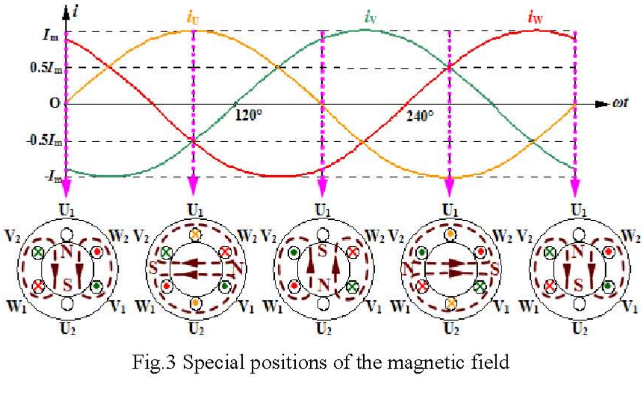


Fig.3 Special positions of the magnetic field

B. *Analysis of rotation magnetic field in air gap inside*

We will let the three-phase coils together into a star connection in the power supply, as shown in Fig. 4(a). Represents the angle between the U-phase coil plane and the reference plane OO 'vertical, the air gap in any of the plane formed by the point P with the shaft with the reference plane OO' α_M, and in the positive direction of the α_M counter clockwise direction.

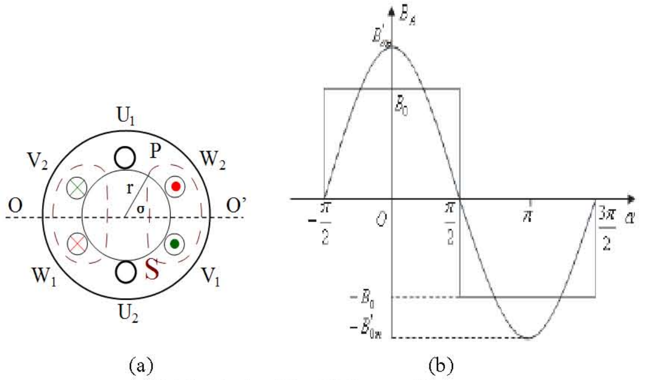
Make the coil U_1U_2 pass through DC I_1', the direction is flowing in from the U terminal, out from U' terminal. Due to the air gap between stator and rotor pole is very small, it can be considered equal to the size of the magnetic induction intensity produced in the air gap. According to the basic knowledge of the electromagnetism magnetic circuit's law, we can get the equation as (1).

$$\begin{aligned} B_0 &= \phi_0 / A = F / AR_m = N_1 I_1' / A(R_{m1} + R_{m2}) \\ &\approx N_1 I_1' / A(2\delta / oA) = \mu_0 N_1 I_1' / 2\delta \end{aligned} \quad (1)$$

where A is the half of the total area of the air gap, φ_0 is the magnetic flux through A, F is the magnetomotive force, it is equal to $N_1 I_1'$, R_{m1} is the coil U_1U_2 magnetic reluctance, it can negligible because of it is far less than the R_{m2}, 2δ is the portion of the total length of the air gap in the magnetic circuit, μ_0 is the permeability of vacuum.

If we assume the reference direction is along the radius and point to the rotating shaft, gas distribution curve in Fig.4 (b) rectangular available space magnetic induction intensity along the air gap of the representation, where B_0 is the amplitude of the magnetic induction intensity generated by the current I_1' of the angle between the air gap, α is a point in the constitution and the shaft the plane with a reference plane OO'. According to the basic knowledge of Fourier series, it is known that the rectangular wave can be divided into several fundamental and harmonic, the fundamental component of the air gap distribution along the air gap is calculated as:

$$\begin{aligned} B'_{1U} &= B'_{0m} \cdot \cos\alpha = 4B_0 \cdot \cos\alpha / \pi \\ &= 2N_1 I_1' \cdot \cos\alpha / \pi\delta \end{aligned} \quad (2)$$



(a) (b)

(a) Analysis of the U phase coil

(b) Distribution of fundamental component along the air gap

Fig.4 Different coils

If the coil U_1U_2 is not accessed to DC I_1', but with sinusoidal AC, the fundamental component of magnetic induction intensity is as:

$$\begin{aligned} B_{1U} &= B'_m \sin\omega_1 t\cdot\cos\alpha \\ &= 2\mu_0 N_1\sqrt{2}I_1 \sin\omega_1 t\cdot\cos\alpha/\pi\delta \end{aligned} \tag{3}$$

By the equation (3) representation of the magnetic field is called the pulsating magnetic field, in which B_m' is a fundamental component of the amplitude of pulse magnetic field generated in the air gap of the sinusoidal current. Obviously, if the coils are communicated with three-phase symmetrical alternating current, the V_1V_2, W_1W2 coil generate the magnetic induction intensity of the fundamental wave component can be expressed as:

$$\begin{aligned} B_{1V} &= B'_m \sin(\omega_1 t+120^\circ)\cdot\cos(\alpha+120^\circ) \\ &= 2\mu_0 N_1\sqrt{2}I'_1 \sin(\omega_1 t+120^\circ)\cdot\cos(\alpha+120^\circ)/\pi\delta \end{aligned} \tag{4}$$

$$\begin{aligned} B_{1W} &= B'_m \sin(\omega_1 t+240^\circ)\cdot\cos(\alpha+240^\circ) \\ &= 2\mu_0 N_1\sqrt{2}I'_1 \sin(\omega_1 t+240^\circ)\cdot\cos(\alpha+240^\circ)/\pi\delta \end{aligned} \tag{5}$$

The magnetic induction intensity in the air gap can be expressed as:

$$\begin{aligned} B_1 &= B_{1U}+B_{1V}+B_{1W} \\ &= B'_m[\sin\omega_1 t\cdot\cos\alpha+\sin(\omega_1 t+120^\circ)\cdot\cos(\alpha+120^\circ) \\ &\quad +\sin(\omega_1 t+240^\circ)\cdot\cos(\alpha+240^\circ)] \\ &= 3B'_m\sin(\omega_1 t-\alpha) \\ &= 3\sqrt{2}\mu_0 N_1 I_1\sin(\omega_1 t-\alpha)/\pi\delta \end{aligned} \tag{6}$$

Therefore, air gap magnetic induction intensity B_1 in the form of waves along the air gap rotation, from figure 1 we can see, magnetic induction intensity wave propagation distance is $x=r\cdot\alpha$, magnetic induction intensity direction along two opposite direction of radius.

Based on the above results, we can come up with that the magnetic induction strength reaches x and the time t can be expressed as:

$$\omega_1 t - x/2 = \pi/2 \ , \quad x = (\omega_1 t - \pi/2)r \tag{7}$$

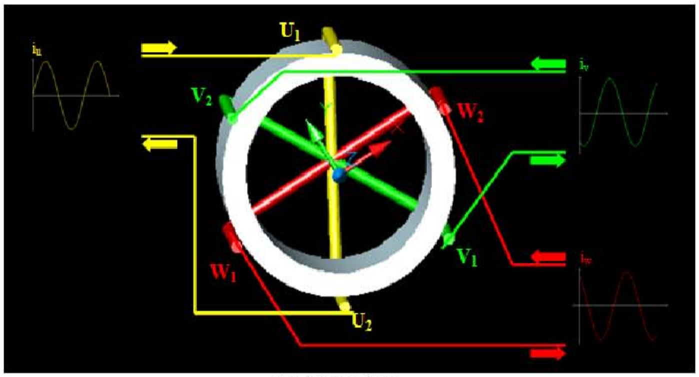
Therefore, the magnetic field in the air gap of the wave propagation velocity and angular velocity can be expressed respectively as:

$$v = dx/dt = \omega_1 r \ , \quad \beta = v/r = \omega_1 \tag{8}$$

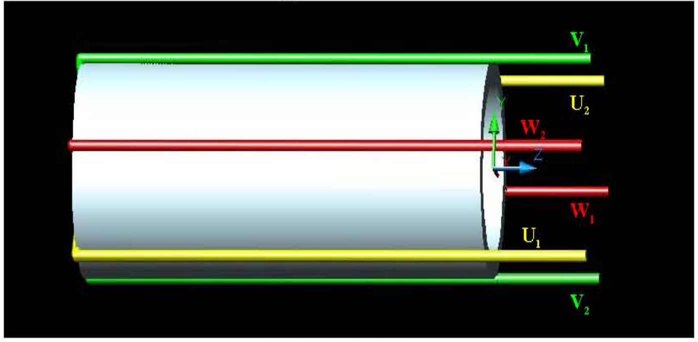
From equation (8), we can find that if the frequency of the rotation magnetic field is not too high, the rotation angular velocity of magnet field, will as same as the microrobot with a pair magnetic, is equal to the alternating current frequency.

C. *Design of a rotation magnetic field model*

Based on the above theories, we will create the rotation magnetic field model platform structure as shown in Fig. 5.



(a) Main view



(b) Lateral view

Fig.5 Structure of the proposed magnetic field model platform

III. CHARACTERISTIC OF MICROROBOT IN THE NEW DEVELOPED MAGNETIC FIELD MODEL

A. *The Structure of Microrobot*

Fig. 6 shows the structure of the prototype of wireless microrobot which consists of two main parts. In order to ensure the balance of the microrobot, we developed a completely symmetrical structure, which can achieve the same dynamic characteristics, too. In the main body of the microrobot, it just contains a piece of permanent magnets, so we can get a more compact structure.

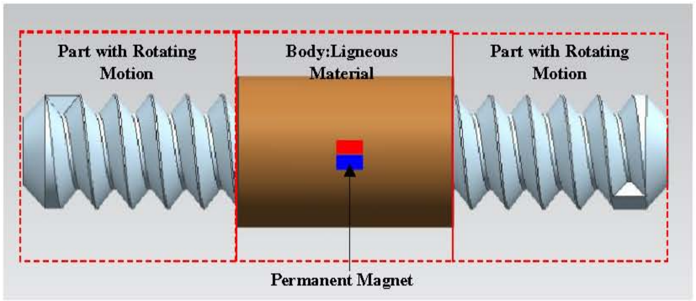
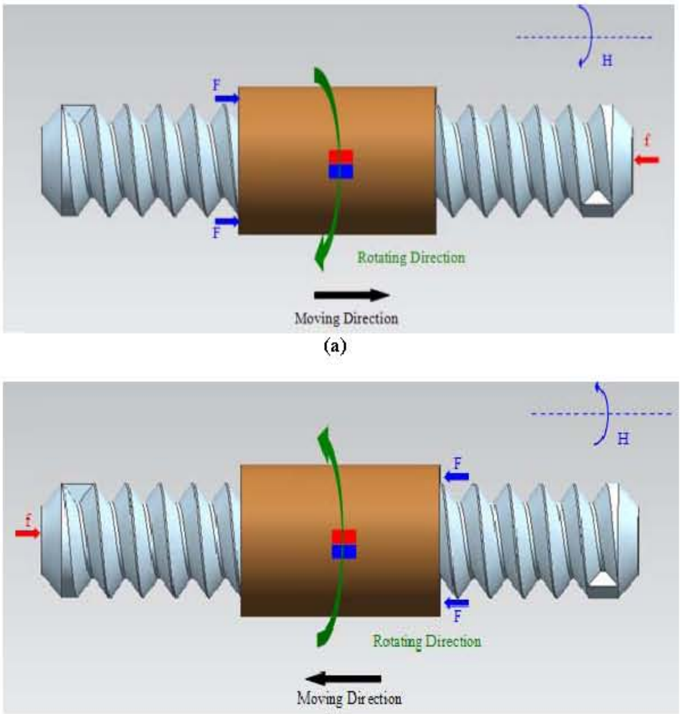


Fig.6 Basic structure of the proposed microrobot

B. *The Characteristic of Microrobot*

The microrobot adopts symmetrical spiral structure, and has same direction of the thread. Base on the microrobot screw driver principle and the spiral driving characteristics have been discussed in the past study [13]. When three-phase alternating currents flowing into the coil in a positive sequence, the characters of microrobot is shown in Fig. 7(a). The permanent magnet will rotate following the rotation magnetic field, through the spiral structure, to propel it forward. We can change the order of any two-phase currents, so an opposite direction of rotation magnetic field can be obtained immediately. Then the microrobot will be in the opposite direction of the rotating screw, and get an effective force to the opposite direction shown in Fig. 7(b). It can be known that the moving speed of the microrobot can be controlled by adjusting the frequency of the input three-phase currents.



(a)

(b)

Fig.7 Characteristics of the proposed microrobot

IV. MOTION CHARACTERISTICS OF MICROROBOT IN THE ROTATION MAGNETIC FIELD MODEL

Experimental results of the rotation magnetic field density are shown in Fig. 8. For the sake of simplicity, we select the cross-section of polar calculation. Since the air gap is small, at this time, our ideal that gap is a circle, the center at the origin of coordinates, z coordinate is to represent the magnetic induction intensity B_1 size, and it represents the direction of B_1 that pointing at the center of a circle or back to the center of the circle. In order to facilitate the simulation, we assume the maximum value $3\sqrt{2}\mu_0 N_1 I_1 / \pi\delta$ of B_1 is 1, so that the $B_1 = \sin(\omega_1 t - \alpha)$.

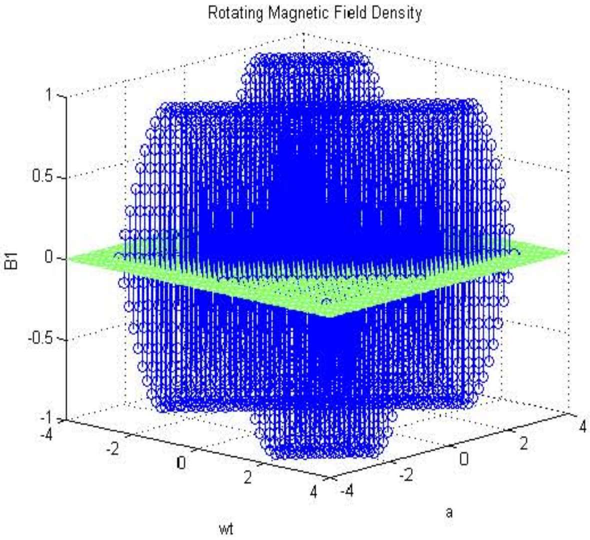


Fig.8 Simulation of the developed 3D rotation magnetic field density

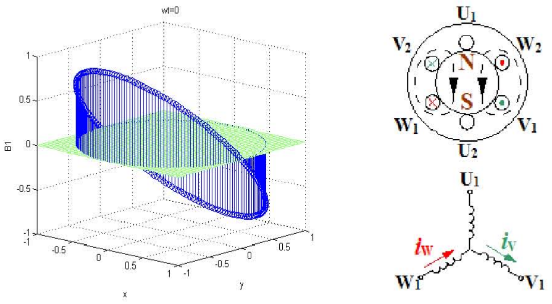
The rotation magnetic field density in a unit of magnetic field strength has been shown in the Fig. 8, which is the rotation magnetic field density in a whole circle. Besides that, we also simulate some moments in a circle, and find some special moments in it.

In the simulations, there are four important moments in a circle in our study, where are ωt=0, ωt=π/2, ωt=π, ωt=3π/2. At these four moments, the rotation magnetic field will achieve vertical and horizontal states just right. Fig. 9 shows four moments in a circle of the three-dimensional rotation magnetic field strength and the three-phase currents phase of the magnetic induction as well as microrobot corresponds to the positions in the pipeline. The microrobot will follow the magnetic field to spiral motion in the pipe, which we have proposed firstly.

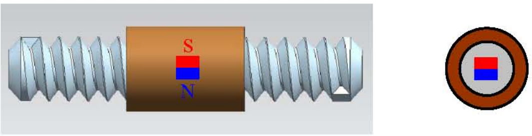
We have simulated the rotation magnetic field in four main moments of a circle, and we can infer the position of the mircorobot in the pipe based on the equation (8). In addition, we can get the rotational frequency of microrobot is as same as the rotation magnetic field easily. So we can control the moving speed of microrobot just by changing the frequency of the rotation magnetic field in a certain range, which is the frequency of the three-phase currents.

In order to analysis the characteristic of the proposed microrobot in the pipe better, we then cut the 3D view along the x, y coordinates of (0,1) in Fig. 9, obtain 2D view corresponding moment (α=0), as shown in Fig.10, where the x axis represents α, y axis represents B_1. We can get the changes in the magnetic field strength, so we can study on the rotation magnetic field more clearly.

The simulations have proved the intensity distribution of the magnetic field in the space of the rotation magnetic field. In a cycle, the overall magnetic field distribution to verify the presence of a rotation magnetic field and the microrobot motion and position in the pipe. The magnetic field strength is related to the three-phase input currents' amplitude.

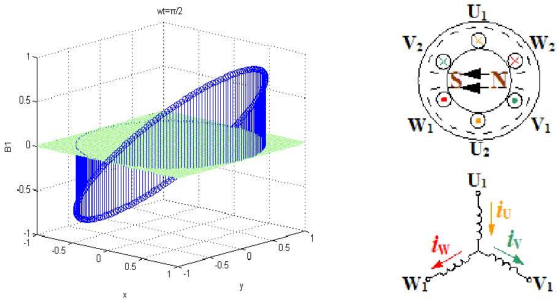


The current state of rotation magnetic field distribution

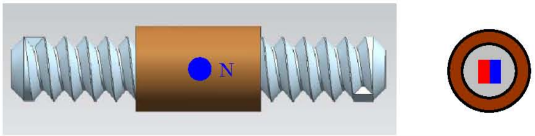


Main view of microrobot Left view of microrobot

(a) ωt=0

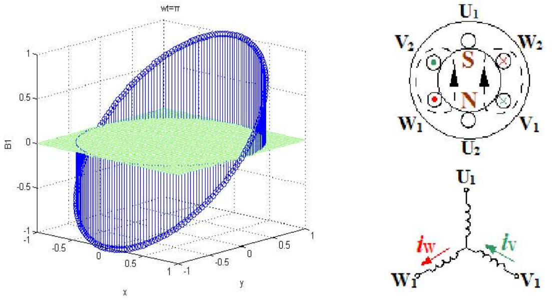


The current state of rotation magnetic field distribution

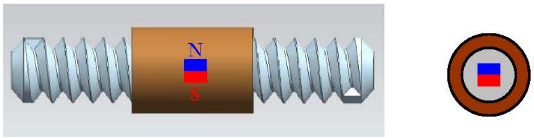


Main view of microrobot Left view of microrobot

(b) ωt=π/2

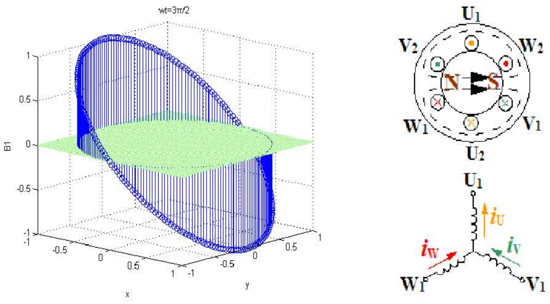


The current state of rotation magnetic field distribution

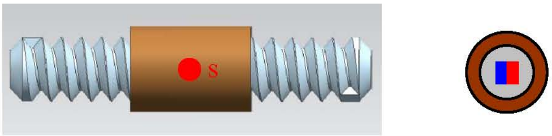


Main view of microrobot Left view of microrobot

(c) ωt=π



The current state of rotation magnetic field distribution



Main view of microrobot Left view of microrobot

(d) ωt=3π/2

Fig.9 Corresponding positions of the microrobot and state distribution of the rotation magnetic field in the four main moments:
(a) ωt=0 , (b) ωt=π/2, (c) ωt=π, (d) ωt=3π/2

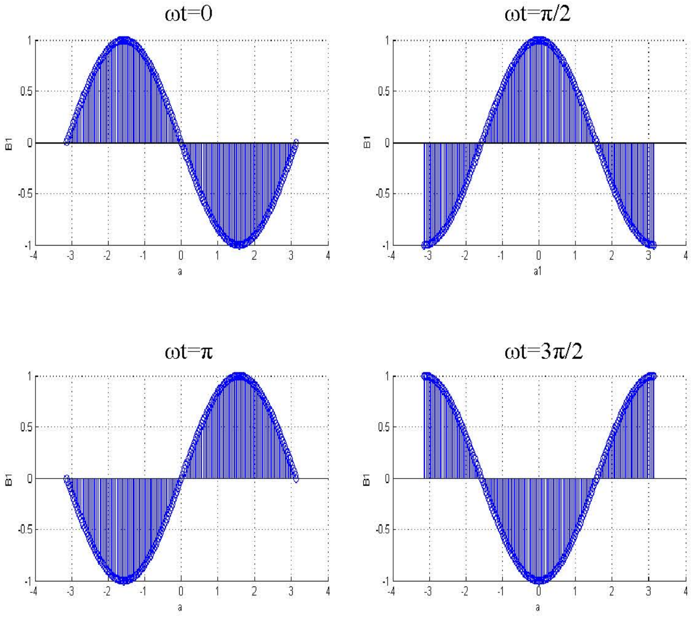


Fig.10 The panorama of 3D magnetic field

V. CONCLUSIONS AND FUTURE WORK

We have proposed a wireless micro in-pipe robot driven by rotation magnetic field. The robot mechanism is simple, in a compact structure and works reliably. Base on the screw driving mechanism, theoretical analysis and software simulation, we establish a rotation magnetic field model. The theoretical analysis and simulations above have the guiding significance to the development of the wireless microrobot control. We also simulate some characteristics of the rotation magnetic field model, and verify the feasibility of the new model and the dynamic characteristics of a microrobot in it.

The new external rotation magnetic field of actuation system provides a new probing approach for further research on wireless microrobot in biological and medical field.

In the future, we will focus on optimizing the design and energy supply of the wireless microrobot further. In addition, we need to build the new model platform and get some quantitative calculations, such as what is the speed of microrobot. How is the speed related to the magnetic field (intensity, frequency, etc). So it will be necessary to design and use an electromagnetism sensor to determine the location of the microrobot in a pipe and for accurate control of speed and position of the microrobot. 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 applying for the microsurgery of blood vessels and in minimally invasive medical procedures.

REFERENCES

[1] S Sudo, S Segawa, T Honda, “Magnetic Swimming Mechanism in a Viscous Liquid”, Journal of Intelligent Material Systems and Structures, Vol.17, No.8-9, pp.729-736, 2006.

[2] K Berk, K Vollmers, B Nelso, “Modeling and Control of Untethered Biomicrorobots in a Fluidic Environment Using Electromagnetic Fields”, The International Journal of Robotics Research, Vol.25, No.5-6, pp.527-536, 2006.

[3] Guo S, Pan Q, Khamesee M B. “Development of a novel type of microrobot for biomedical application”. Microsystem Technologies, Vol. 14(3), pp. 307-314, 2008.

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

[5] Honda T, Sakashita T, Narahashi K, et al. “Swimming properties of a bending-type magnetic micro-machine”. Journal of Magnetics Society of Japan, Vol. 25, Nos. 4(2), pp.1175-1178, 2001.

[6] T Mei, Y Chen, G Fu and D Kong, “Wireless Drive and Control of a Swimming Microrobot”, Proceedings of the 2002 IEEE International Conference on Robotics and Automation, Vol.2, pp.1131-1136, 2002.

[7] S Guo, Y Sasaki, T Fukuda, “A New Kind of Microrobot in Pipe Using Driving Fin,” IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Vol. 2, pp.667-702, 2003.

[8] S Guo, Q Pan, “Mechanism and Control of a Novel Type Microrobot for Biomedical Application”, Proceedings of the 2007 IEEE International Conference on Robotics and Automation, pp.187-192, 2007.

[9] S Sudo, S Segawa and T Honda, “Basic Research on the Medical Micro-Robot using a Permanent Magnet and Alternating Magnetic Field”, Proceedings of Second International Symposium on Aqua Bio-Mechanisms, Honolulu, Hawaii, CD-ROM 1-6,2003.

[10] S Guo, Q Pan, “Development of Multifunctional Wireless Microrobot for Biomimedical Application”, Proceedings of the 2007 IEEE/ICME International Conference on Complex Medical Engineering, pp.1836-1841, 2007.

[11] Pan Q, Guo S, Okada T. “Development of a wireless hybrid microrobot for biomedical applications”, Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on IEEE, pp.5768-5773, 2010.

[12] Qinxue Pan, Shuxiang Guo, Takuya Okada, “A Novel Hybrid Wireless Microrobot”, International Journal of Mechatronics and Automation, Vol.1, No.1, pp.60-69, 2011.