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Motion Performance of a Novel Fan Type Magnetic Microrobot in Pipe

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Abstract- **Various type capsule robots are widely used in clinical medicine field because of their small size, light weight and painless characteristics. Meanwhile, the size limitations have become the biggest challenges for researchers to develop it for the practical applications. During the clinical surgery, a single capsule robot is difficult to achieve versatility in a single purpose. To achieve the goal, we did a lot of research in advance: the development of the structure and achieve different movement function, evaluation of the inlet part with the fan drive motion. In this paper, the whole operations system will be carried out and be introduced theoretically. Then, the structure of new type microrobot and its movement principle in horizontal and vertical directions will shows in the third chapter, Moreover, the simulation will be carried out to analysis how the new type microrobot runs in pipe. Finally, the comparison between experiment results and simulation results will be discussed and the feasibility of the design will be discussed.**

Index Terms – Magnetic actuated microrobot, Magnetic electronic field, Fan drive, simulation.

I. INTRODUCTION

Capsule microrobots are widely used in modern medical field such as clinical surgery or examination. Owing to the great potential of capsule microrobots, mechanisms and locomotion have been developed for decades. In details, these robots can be used in to clearing blood clots or carrying the drug to a desired position of the wound, even the larger types can cleaning the pipe under the road [1]-[4]. The development of it helps medical staff to find the exact position without wound, especially with the development of hardware technology in recent years, the volume problem of the capsule robot can be solved very well. The volume problem during the development of the robot is the biggest challenge to the researchers, the maximum length is no more than 30mm. These wireless capsule microrobots are able to reach narrow regions, such as the blood vessel and small intestine, which are not possible with conventional endoscopes. Therefore, the size of each part on the robot limits the function module development, the previous research in our laboratory in this field proposed various type microrobots, a promising new approach for locomotion in the laminar regime is propeller or screw propulsion, where actuated by external electric magnetic field module, the robots rotate inside the patients' tissues [5], [6]. The majority of these robots are wireless controlled, this kind of robot has a stable motion performance, including multi-directional motion. Then we has proposed the hybrid type motion microrobot, it can change the motion type according to different environment [7]-[9]. But these robots also have some disadvantages, the most of the cable driven microrobots can not achieve long distance movement inside human body, it would take uncomforts to the patient. As for the structure design of wireless microrobot in previous research, it may injured the patient's intestine when they move inside of human body, also by the reason of the limitations of mechanical structure limits the development of function module, these robots can not achieve multi functions when they working. So that we need to create a new type magnetic microrobot which has a space to design the function module inside the robot and the protection of the patient's tissue is also the main work of this research [10]-[12].

II. MAGNETIC OPERATION SYSTEM

The magnetic actuated microrobot is driven by electrical magnetic field, in previous researches, various types of electromagnetic actuation systems have been developed to manipulate the magnetic microrobot in human tissue, e.g., intestinal tract, blood vessels and stomach. Due to the structure of the electromagnetic actuation system, the locomotive range of the microrobot is limited [13]. Therefore, we proposed a novel electromagnetic actuation system, Fig.1 shows the whole electromagnetic actuation system [14], [15]. On the master side, a visual image inside a pipe is monitored by a camera and displayed on a monitor. Using a Phantom Omni device, control instructions are sent out and transmitted to the control unit, which with an amplifier, a DC power supply module and a control circuit. Upon receiving instructions, the slave mechanisms (three-axis Helmholtz coils) generate an external rotating magnetic field to control the different kinds of movements

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TABLE I
PARAMETER OF EACH AXIS

Dimension of the three-axes Helmholtz coils			
	X axis	Y axis	Z axis
Resistance (Ω)	2.4	3.3	4.5
Wire Diameter (mm)	1.5	1.5	1.5
Inner diameter (mm)	284	350	400
center-to-center distance (mm)	150	175	200
Turns per coil (times)	125	150	180

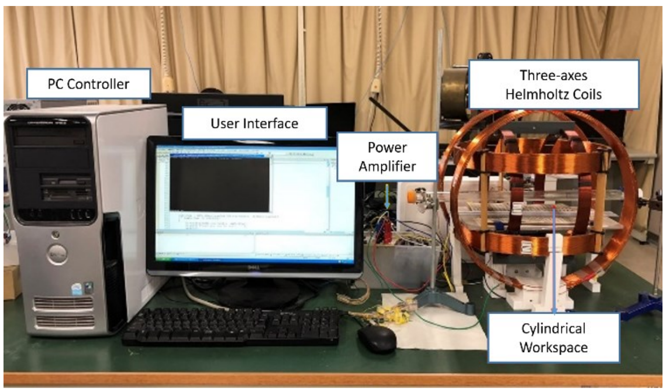


Fig. 1 Experimental operation system.

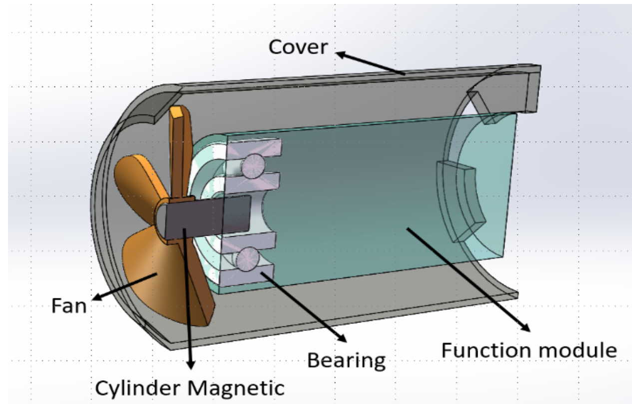
of the magnetic actuated microrobot. The monitor can also display the data calculated from the magnetic sensor array for obtaining the real-time position of the robot. The positioning module is playing the role to accomplish a close-loop control and make ensure the robot achieves the task [16]. Consequently, the doctor appears to accurately control the position and posture of the wireless microrobot in the human body.

During the examination, to make ensure the robot moves in in different directions of the same force and magnetic torque, we need a controllable magnetic field module in three-dimensional space, the role of three-axes Helmholtz coils in the progress is to supply the power of rotation for the magnetic robot. [21] The parameters of each axis have been shown in Table I.

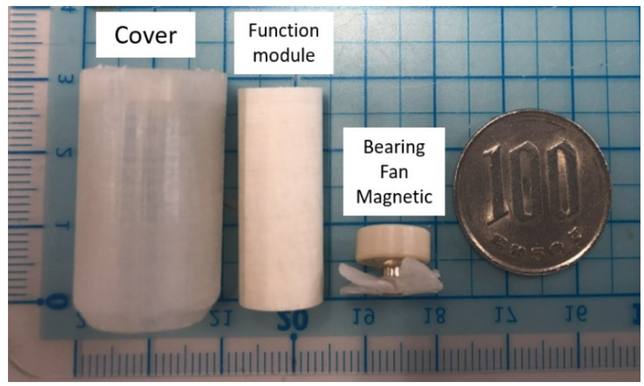
As for the structure of three-axes Helmholtz coils, there is a couple of coils on each axis, with the centre distances of each pair of coils are denoted by L. When L is equal to coils radius R, and the electrical current in each pair is the same. The formula for magnetic flux density is shown in equation (1) [6], [17]:

$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 N I}{R} \tag{1}$$

where, B is the magnetic flux density at any point between the couple axis of the Helmholtz coils. R is the radius of the coils. μ_0 is permeability of vacuum. N is the turns number of each coil and I is the electrical current of coil. By inputting the control signals to the three-axis Helmholtz coils, a rotational or undulation magnetic field is generated to control



(a)



(b)

Fig.2 Physical scale structure diagram. 3D model of Fan Type Microrobot.

the permanent magnetic microrobot moves in any directions [18].

While the microrobot which has a magnet as an actuator inside driven by an external magnetic field running in pipe, the propulsive force and magnetic torque are supplied by the external magnetic field. The microrobot can rotate due to the magnetic torque T. The magnetic force F and magnetic torque T acting on the magnet inside the external magnetic field generated by the three-axes Helmholtz coils is given by the equations (2) and (3) [19]:

$$F = V(M \cdot \nabla) \times B \tag{2}$$

$$T = VM \times B \tag{3}$$

where, B is magnetic flux density, M is the magnetization of the magnet and V is the volume of the magnet.

III. STRUCTURE DESIGN OF FAN TYPE MICROROBOT

A. Structure design

The mechanical structure design (3D model) is shown in Fig. 2(a), physical scale diagram is shown in Fig. 2(b). In order to protect the patient's tissue, firstly we kept the original design on the cover part. When the internal structure rotated by the external rotating magnetic electronic field, the outside cover won't rotating at the same time, this design is

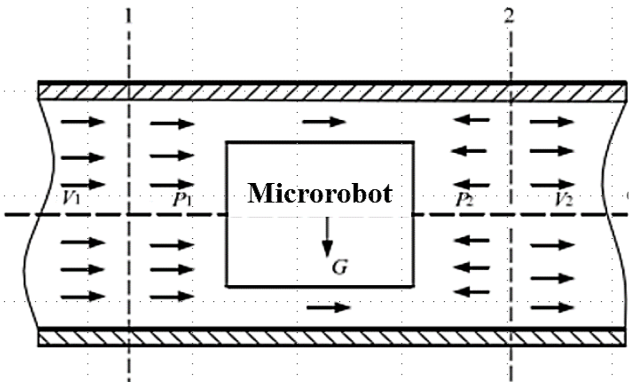
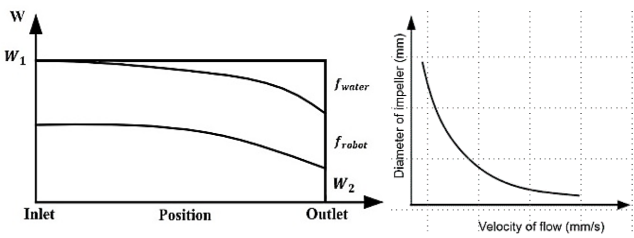


Fig. 3 Theoretical model of the robot in horizontal direction.



(a) (b)

Fig. 4 (a) Total mechanical energy of movement (b) Relationship between diameter of blade and flow velocity.

used to keep the rotating driven module away from the tissue. As for the inside part, we add the driven module with four fan blade. Comparing with the proposed microrobots, the new design has a benefit is that it used vertical directional space to provide the propulsive force for the microrobot. The remaining space can be used for the development for the function module on further research.

B. Movement principle

When the microrobot moving in horizontal direction, Conservative Bernoulli equation (4) as:

$$\frac{1}{2}\rho v^2 + \rho g h + p = \text{constant} \tag{4}$$

where ρ is density of liquid, v is the velocity of flow, g is gravity acceleration, h is height of the microrobot, p is the pressure of the liquid.

In actual operation, expect to being affected by gravity and fluid pressure, the friction force and fluid viscosity will also effect on the moving microrobot, which leads to the loss of mechanical energy. The motion diagram is shown in Fig. 3. Therefore, the Bernoulli equation should be changed as equation (5):

$$W_1+\frac{P_1}{\rho g}+\frac{{v_1}^2}{2g}=W_2+\frac{P_2}{\rho g}+\frac{{v_2}^2}{2g}+W_{water}+W_{robot} \tag{5}$$

where W is mechanical energy, p is the pressure on each part, v is the velocity of inlet and outlet part.

So that the dynamic pressure can be written as equation (6):

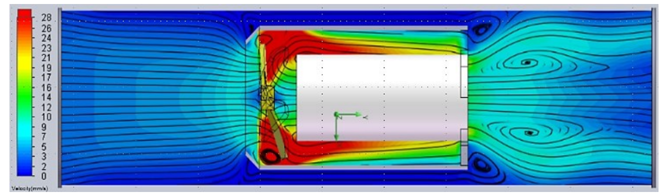


Fig. 5 Simulation result of fan blade rotating on forward direction.

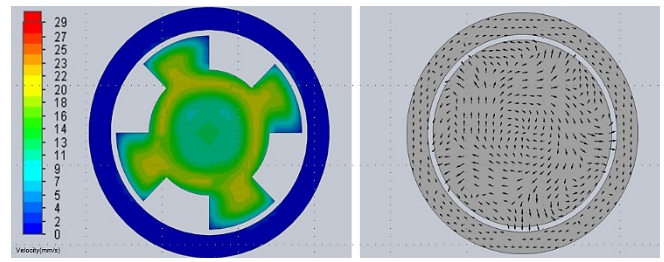


Fig. 6 Simulation result of outlet and eddy on X-Y axis

$$P_d = \frac{1}{2}C_D \times \rho({v_{flow}}^2 - {v_{robot}}^2) \tag{6}$$

where C_D is the coefficient of liquid, v is velocity on inlet and outlet part.

Finally the mechanical energy of the robot can be written as equation (7):

$$W_{robot} = \frac{1}{\rho g}(P_1 - P_2)+\frac{1}{2g}v^2 \tag{7}$$

And the totally mechanical energy is shown in Fig. 4(a).

The variable quality inside microrobot is equal to the inlet quality at fan part, then the mass conservation equation (8):

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0 \tag{8}$$

where v_x, v_y and v_z are the velocity component at x, y and z axis. The movement of the flow has impact on the fan blade, eliminate stress from the equation, we can get the differential equation of the flow movement with velocity component and pressure, shows in equations (9) to (11):

$$\frac{dv_x}{dt} = f_x - \frac{1}{\rho}\frac{\partial p}{\partial x} + vVv_x \tag{9}$$

$$\frac{dv_y}{dt} = f_y - \frac{1}{\rho}\frac{\partial p}{\partial y} + vVv_y \tag{10}$$

$$\frac{dv_z}{dt} = f_z - \frac{1}{\rho}\frac{\partial p}{\partial z} + vVv_z \tag{11}$$

where f_x, f_y and f_z are the unit quality of the flow at x, y and z directions; v_x , v_y and v_z are velovity component at x, y and z directions; V is the Kinematic Viscosity (m^2/s); p is

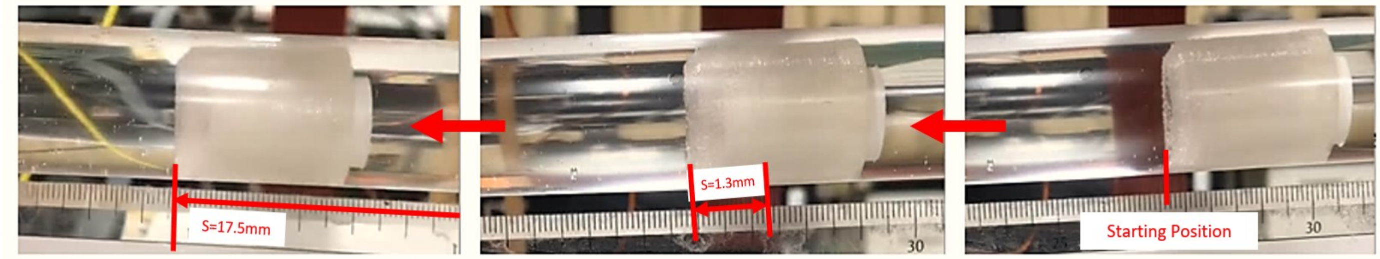


Fig.7 Experiment procedure of Fan Type Microrobot moving in forward direction

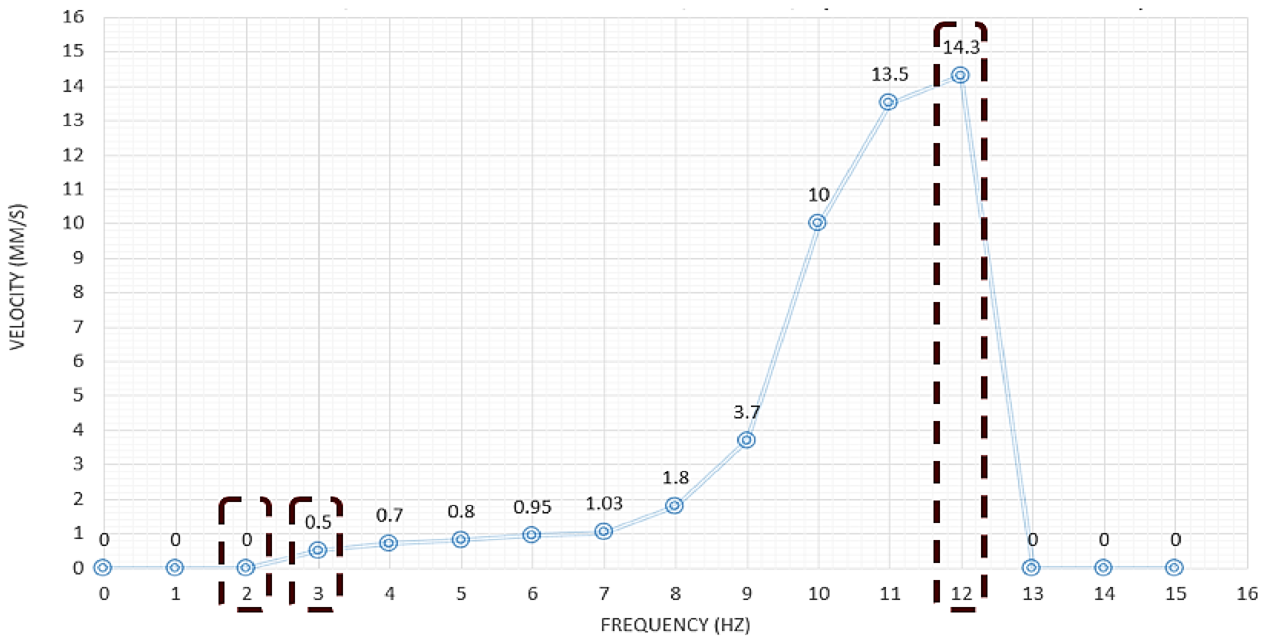


Fig.8 Experiment results in moving forward

dynamic pressure of fluid (pa). The relationship between diameter of blade and flow velocity has shown in Fig. 4(b).

IV. Simulation and Experiment

A. Simulation on fan blade internal structure

In simulation settings, we set the fan blade rotating at 12 rad/s, and simplified model on function part as a wall cylinder. As for the simulation results, shows in Fig. 5, we cut the X-Y axis plan which perpendicular to the z-axis to show the velocity on flow rate around the robot. Finally, the eddy of cross section behind the fan blades is shown in Fig. 6.

B. Experiment of motion performance

The experiment procedure has shown in Fig.7. During the experiment, we adjusted the magnetic field rotating frequency started from 0 to 15 Hz, each step for 1Hz. The experiment platform, three axis Helmholtz coils and its working principle has mentioned in chapter II, as for the environment of the experiment, we did it at room temperature and the liquid we chose water and operation place was PLC pipe with φ 15mm. We kept the capsule microrobot's operating environment and its ownvarious physical indicators at the same level, especially the distance between fan and bearing, it will influent velocity of the flow and robot's own rotating. When the robot arriving at the edge of the magnetic field, we use low magnetic magnet to pull it to the starting point to keep the parameters the same as last step.

V. Results And Discussion

The experiment results of the fan type microrobot moving on forward direction has shown in Fig. 8. We used filler instead of function module, to simulate the gravity of it. At beginning, the microrobot running at 0-2 Hz, the friction force is larger than the propulsive force which proposed by fan blade. 3Hz is the starting frequency of this type microrobot. As for 3Hz to 8Hz, the robot moves unstably with low velocity. With the increasing of rotating frequency of electrical magnetic field, the velocity shows a linear trend, the propulsive force and dynamic pressure push the microrobot moves faster against the friction force and viscous resistance of liquid. Then the sudden increase of velocity shows around 9Hz to 12Hz, and step-out frequency is 12Hz, the velocity decrease to 0 mm/s sharply and stopped. There are still some details to be improved in this experiment, such as the development of the function modules. Then is the withdrawal in each step, even we used low magnetic magnet to pull the capsule microrobot back to starting point, the pulling force will always affects on the internal structure, this inevitable error will still there during the experiment. And we considered the filler as the function part, which means the parameters and variables were seen as the gravity only, the impact of internal structure of function module has not been added in both of the simulation part and experiment. In future research, according to the intestine of human environment, the pipe we used in this research will be changed in to curve pipe, as for the simulating of blood vessel, we will do the experiment in different kinds of environments with flowing liquid created by pump.

VI. Conclusion

Considering the previous research and relative research, the lack of functions and protection during the surgery is a kind of biggest challenge. By this research, we proposed a novel fan type magnetic actuated microrobot, which can provide a working space for the function module in the future research and design. The mathematical model of this type microrobot has been builded, it provided the basis for theoretical research, the velocity shows linear steady increment trend, and starting frequency shows at 3Hz (0.5mm/s) and step- out frequency is 12 Hz (14.3mm/s), which means according to this reliable motion performance, we can develop the function module based on the breakthrough in this research.

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