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Motion Performance Evaluation of a Magnetic Actuated Screw Jet Microrobot

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Abstract - **In this paper, we carried out a series of experiments and evaluations Motion Performance for a Magnetic Actuated Screw Jet Microrobot. Our system consists of three main parts, the power supply section, 3-axes Helmholtz coils are to provide a uniform controllable magnetic field; the simulated intestinal part, a 450mm long ϕ20mm liquid filled pipe; a screw jet microrobot, it consists an O-ring type neodymium magnet and screw structure. We have verified in previous papers that our magnetic actuated screw jet microrobot can run smoothly in a variety of liquid environments (extra degree of freedom that enables various advanced functions such as axial position control), in the following discussion, we will keep the other conditions unchanged, to evaluate the influence of changing the pitch of the screw of the speed. There are many factors affecting the speed, we will also evaluate the effects of viscosity coefficient of different liquids on the velocity.**

Index Terms - Screw jet motion; Difference of pitch& liquid; Rotational magnetic field; Three-axis Helmholtz coils.

I. Introduction

Microrobots have widely biomedical applications and prospects, a variety of capsule robots have been developed, they have different structures and functions to respond different problems and challenges. Capsule robots are replacing traditional endoscopes in clinical field and this situation is becoming popular in recent years.

The traditional cabled endoscope has been applied for many years, there are also many disadvantages of conventional endoscopes, such as it will cause injury to the human body, bring discomfort to the patients. Simultaneously, there are many narrow places in the intestinal, its wired design also limits that it is difficult to reach the depths in the human body. But capsule robot has the advantages that traditional cabled endoscope does not have noninvasive surgery, wireless and smaller volume. At present, the actuation of capsule robots is mostly dependent on intestinal tract peristalsis, or dragging forward by external magnetic field, the former detection time is too long and can not achieve backward motion, the latter one will take pain to the patient [1]-[8].

At present, the function and moving methods of capsule robots are mostly depended on the target area in the gastrointestinal area, some of these types of robots' motion functions are relatively simple, as a tool for diagnosis and treatment, microrobots can be used for tasks such as drug delivery and complex surgical operation [9]-[12].

As mentioned earlier, wireless, small size, is its most prominent advantages, meanwhile developers have to achieve a variety of different functions in a limited space, it's also the biggest challenge which developers have to overcome. As for the magnetic actuated robots which have been developed in Guo lab contain the above advantages [13],[18]-[23].

In this paper, we will introduce as following. Firstly, we will introduce the microrobot and its control system which has been proposed in our laboratory, which includes the drive device, 3-axes Helmholtz coils, the screw jet microrobot's design and its internal structure. Second, we will introduce the robot's driving and working principle, then list the formula. And finally, the experimental part and its analysis on motion performance of different pitch of microrobots [23]-[27].

II. Proposed Magnetically Actuated Microrobot

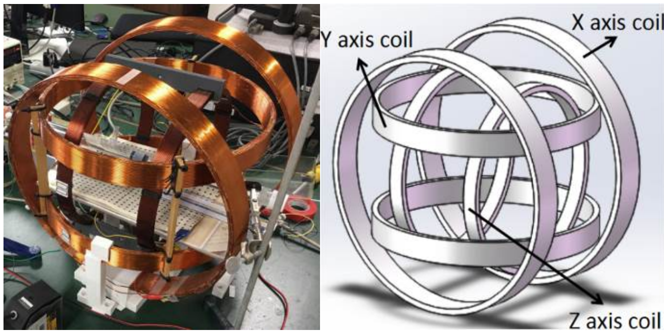
A. *Screw jet microrobotic system*

The system consists of two main parts, a 3-axes Helmholtz coils and a wireless capsule microrobot, in which the 3-axes Helmholtz coils play the role of providing energy, we can also control the speed of microrobot by changing frequency of magnetic field. As for the microrobot, it's a carrier for surgical function, drug delivery and camera function, it runs in the human intestine [28]-[30].

B. *Three-axis Helmholtz coils*

We developed driving systems to realize wireless automatically locomotion of the microrobot. Proposed driving system, it provides power for the movement of the microrobots and working environment. The specific rotation principle of the magnetic field has been discussed in the previous paper [14].

To ensure that the robot in the pipe in different directions of the same force and torque, we need a controllable magnetic field in 3-dimensional space, the role of 3-axes Helmholtz coils is to provide the power of rotation for wireless microrobot, shows in Fig. 1. In addition, the parameter of each axis has shown in TABLE 1.



(a)Practicality photo (b) Simulation model

Fig. 1 Three-axis Helmholtz coils

TABLE 1
3-AXIS HELMHOLTZ COIL PARAMETERS

	Turns N	Coil radius r(mm)	Distance d(mm)	Resistance R(Ω)
X axis	125	142	150	2.4
Y axis	150	175	175	3.3
Z axis	180	200	200	4.5

There is a couple of coils on each axis, the center distance of each pair of coils are denoted by L. When L is equal to radius R, and the current in each pair is the same. The formula for magnetic flux density is shown in equation (1).

$$B_0 = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 NI}{R} \quad (1)$$

where, B is the magnetic flux density, at any point on the axis of the Helmholtz coils. N is the number of turns of coil. I is the current in the coil. R is the radius of the coil [15].

C. *Modeling of microrobot*

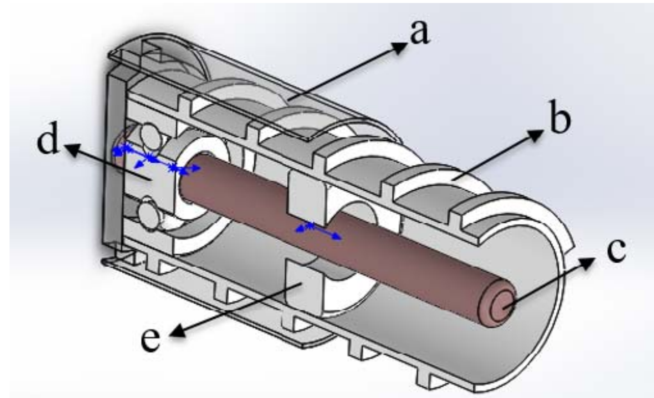
The structure of our microrobot is shown in the Fig. 2. Each part of the robot has been identified. Comparing to the previously developed screw microrobot [16], we added a shell outside the new robot, it can avoid the direct friction in human intestine when the microrobot is rotating [17]. Certainly, the addition of the shell will take a lot of impact on the movement. We will experiment and evaluate the effects of changes in some of the parameters in the experimental section.

D. *Propulsive model and drive principle*

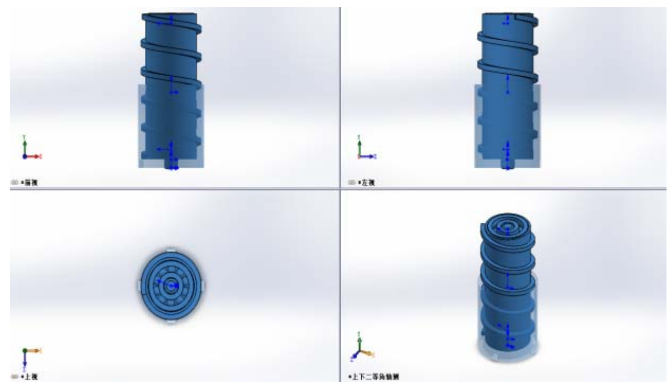
When the robot is running in the human intestine, the propulsive force is produced by the water which is rotated out by screw, at the same time, there will be other forces, such as hydraulic resistance, friction, component force of buoyancy and gravity [18]. According to Newton's second law, we derive the following formula:

$$F_P - F_D \pm F_{\sin\theta} \pm G_{\sin\theta} + m\frac{dv}{dt} = 0 \quad (2)$$

where F_B is buoyancy, F_D is hydraulic resistance, F_P is the



(a) Profile structure. a. Shell, b. Screw, c. Shaft, d. Bearing, e. O-ring type magnet



(b) Three -dimensional model

Fig. 2 Structure of microrobot

propulsive force, G is gravity force, m is the mass of microrobot, v is speed. θ is the angle between the microrobot's movement direction and the horizontal direction.

III. EXPERIMENT FOR MOTION PERFORMANCE

Different pitch microrobot

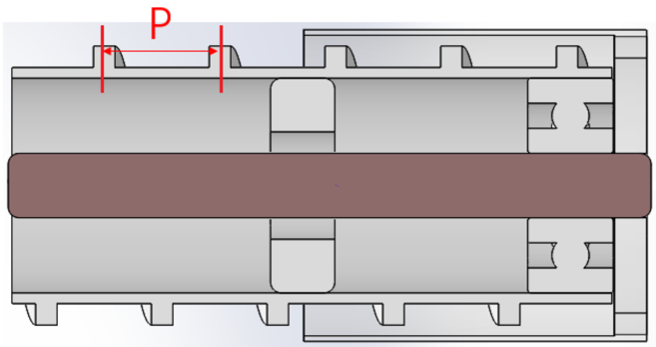
The movement speed of the robot is mainly controlled by the external magnetic field, the robot's own parameters will also have a certain impact on the performance of movement. Here we will change the pitch and keep other parameters such as the shell, liquid constant to measure and evaluate the relationship between speed and frequency of different pitch screw microrobots.

Different Pitch microrobots have shown in Fig. 3. We kept the length of the robot in the case of the same and made four different pitch microrobots. Pitch is the distance of two screw center points, the pitch (P) is 14 mm, 9.3 mm and 7 mm respectively while keeping the overall length (L) of the internal part is 28 mm.

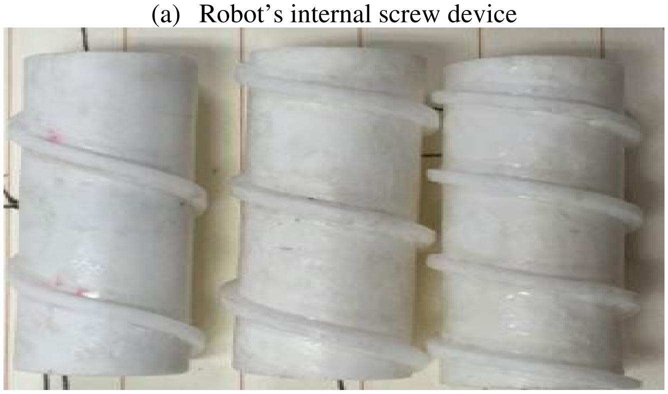
IV. EXPERIMENTS AND RESULTS

A. *Motion performance of different pitch robot*

In this experiment, there are many variables or factors



(a) Robot's internal screw device



(b) Picture of different pitch screw device

Fig. 3 The cross section and the physical photo of the internal structure

that affect the experimental results, each time when we replace a different robot, an error is generated, we did our best to minimize this error during the experiments.

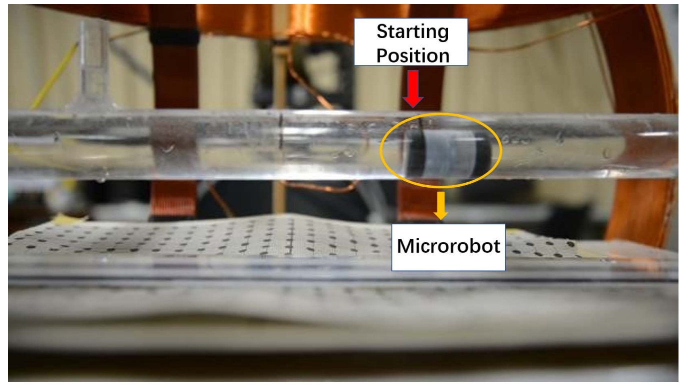
As for being able to infer the relationship between speed of different pitch microrobots and magnetic flux density while changing frequency, we control the shell, inner shell, O- ring type magnet and other parameters remain unchanged.

We also keep the current same to control the magnetic field in the same condition. The relationship between the magnetic flux density changing frequency and the speed of the microrobot has shown in Fig. 5.

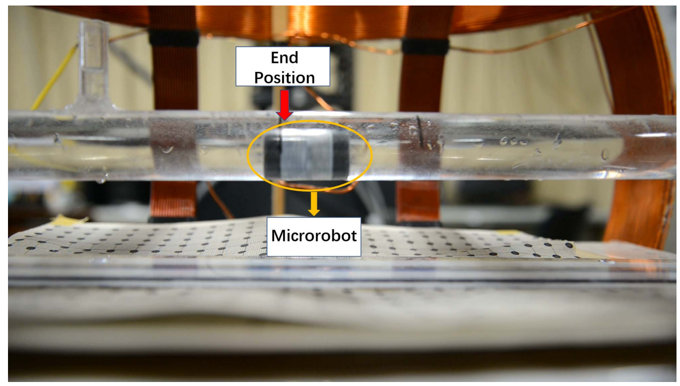
The equation (3) is the relationships between moving speed and frequency of the magnetic flux density of different pitch microrobots. where, v is the moving speed and f is the magnetic flux density changing frequency:

$$v = -0.00085f^3 + 0.022f^2 + 0.0694f + 0.092 \quad (3)$$

In the experiments, we adjusted the magnetic flux density changing frequency from 0 to 16 Hz. We controlled the magnetic flux density with each step 0.5 Hz and then measured the speed of the microrobot on 3 different pitch. The experimental results and the fitting curve shows the relationship between the magnetic flux density changing frequencies and speed is linear before 15 Hz. The speed will increase as the frequency increases and it reached the maximum speed at 5 Hz and began to fluctuate. When the robot was moving at high frequency, there are many factors that can cause the movement to be unstable, such as imbalance, resonance and other factors.



(a) Capsule the robot at the starting position



(b) Capsule the robot at the final position

Fig. 4 Experimental process diagram

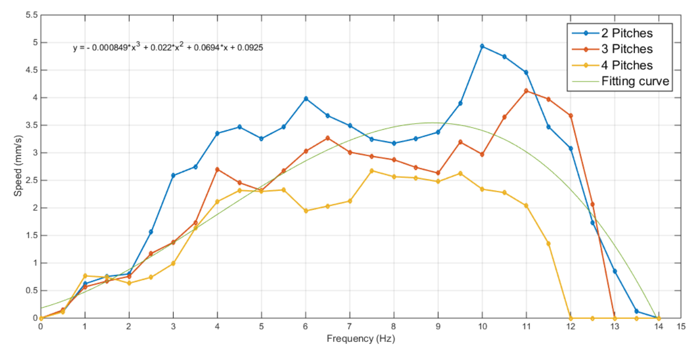


Fig. 5 Relationship between speed and frequency of different pitch

When the frequency at around 10 Hz, the speed began to decrease significantly. We can also get the conclusion that in reasonable circumstances, microrobot of 2 pitch's speed is faster than the speed of 3 pitch's and 4 pitch's. The more the pitch is, the sooner the move stops, after the 14 Hz the microrobot did not move in the pipe because the microrobot can no longer rotate continuously, we suspected that one of the reasons is resonance, it is related to natural frequency, microrobot's weight and other parameters. We will focus on the study of the reasons for the resonance in the future.

B. *Motion performance in different liquid*

In the experiment about different liquid, we kept the temperature at

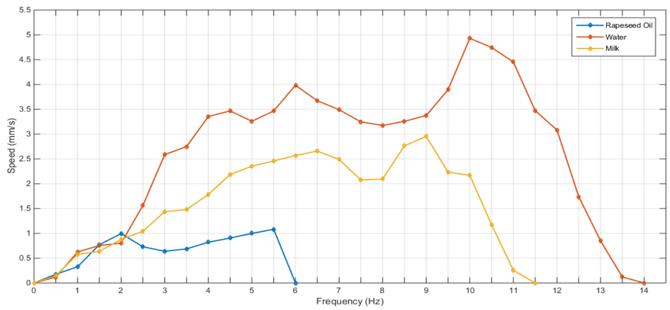


Fig. 6 Movement speed of the robot in different liquids

around room temperature, we did three different kinds of liquids, water, milk and rapeseed oil. By the experimental results of Fig. 6, we can see the speed trend of the robot in different liquid, is same as the experimental result as water. But different liquids have different liquid properties, the hydraulic resistance will change with drag coefficients.

$$F_D = C_D A \rho \frac{v^2}{2} \tag{4}$$

where F_D is hydraulic resistance, C_D is the drag coefficient of the liquid, A is the contact area, ρ is the density of the liquid, v is speed of robot.

In equation (4), C_D is depended on many parameters, such as the shape of microrobot, the viscosity coefficient of the liquid and other parameters. So, if we want to get C_D, we need get the information of Reynolds number (Re) of liquid. Reynolds is given in equation (5)

$$Re = \frac{\rho v D}{\mu} \tag{5}$$

where is the density of the fluid, v is the speed of microrobot, D is the diameter of microrobot, μ is the viscosity coefficient of the liquid. From equation (4), in the case of the same propulsion, we can know that with the increasing of speed, hydraulic resistance will become larger, this is the reason of microrobot's speed is not infinitely increasing. We also found that we can get more stable experiment results in the liquid which has higher drag coefficient. There are many factors that affect the drag force, such as resonance, with the increasing of speed, C_D will be changed very complexly. This is a certain deviation between result of the experiment and the discussed the theory.

IV. Conclusion

In the published papers, we have analyzed the driving device, principle and movement characteristics, discussed the effect on different flow (by changing the Height). And in this paper, we simply introduced a wireless capsule microrobotic system and its working principle. We also evaluated the motion performance of robots with different pitch with different motion characteristics, the experimental data shows that the 2 pitch microrobot moves faster than the other two, and the experimental results also become a linear, it has played a positive role in evaluating our athletic characteristics, the difficulty of this experiment is to control the other variables when replacing the robot.

In the second progress of experiment, we evaluated the effect on drag coefficient, this experiment verifies our previous theory that speed will not infinitely be increasing, because the propulsion force will be decreased with the increasing of hydraulic resistance.

During the progress of experiments, we met some problems which have been found before, it's a big challenge for us, for example, when the microrobot is moving at high frequency, it will stop and shake at that place. We found out one of the reasons is the relationship between propulsion force and hydraulic resistance that has shown in equation (2), another reason is resonance, we will focus on this problem in the future research.

Acknowledgment

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