Micro swimming mechanisms propelled by external magnetic fields

著者	石山　和志
journal or publication title	IEEE Transactions on Magnetics
volume	32
number	5
page range	5085-5087
year	1996
URL	http://hdl.handle.net/10097/47750

doi: 10.1109/20.539498

Micro Swimming Mechanisms Propelled by External Magnetic Fields

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Abstract— A new type of micro swimming mechanism is proposed for microrobots working in water. It is composed of a small magnet attached to a spiral wire. An external alternating magnetic field causes the magnet to rotate due to magnetic torque. As a result, the mechanism can swim propelled by waves traveling along the spiral. The swimming velocity increases linearly with increasing excitation frequency, and the increasing rate depends on the shape of the spiral. The experimental velocity agreed with the calculation result based upon Lighthill's theory.

I. Introduction

Recently various kinds of mobile microrobots have been proposed for industrial and medical applications. In particular, a swimming microrobot is expected to be applied for inspection, maintenance and treatment of small pipes such as in a radiator and a blood vessel. Although a few studies have so far been made on swimming microrobots[1], they have power supply cables which disturb the actuation in a microworld. The power supply to the microrobot should be wireless.

In addition, it must be noted that the Reynolds numbers *Re* (that is, the ratio of inertial force to viscous force) of small swimmers are very low. A typical example is the Reynolds numbers of the micro-organisms whose size is less than 1 mm, which are on the order of 1 or less[2]. In this case, the force involved in propulsion is predominantly viscous and the inertia can be neglected. This rule may apply to microrobots around 1 mm in size or less as well. It is necessary to develop a swimming mechanism suitable for low Reynolds number.

In order to realize a wireless-operated swimming microrobot with $Re < 1$, we proposed a spiral-type swimming mechanism which imitated a bacterial flagellum. The cm-size model fabricated could be remotely operated by external magnetic fields. This paper describes the structure, principle, and basic swimming characteristics.

II. Structure

Fig.1 shows a schematic view of the cm-size model of the spiral-type swimming mechanism. It is composed of a cubic

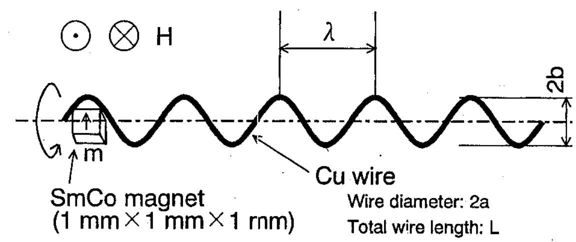

Fig.1 Schematic view of the spiral-type swimming mechanism.

$SmCo_5$ magnet attached to a spiral with diameter $2b$ and linear wavelength λ. The spiral is made of a copper wire with diameter $2a$ and total length L when stretched straight. The dimension of the spiral is determined by the four parameters: λ, $2b$, L and $2a$. In this experiment, we fixed $2a = 0.15$ mm and examined the effects of changes in other parameters on the swimming velocity. The cubic magnet, with each side of 1 mm, is magnetized along the direction normal to the axis of the spiral. When either an alternating magnetic field or a rotational magnetic field is applied in the plane normal to the axis of the spiral, the magnet rotates due to magnetic torque. As a result, spiral waves propagate along the wire tail and then the mechanism can propel itself in the direction opposite to that of the wave propagation. The swimming direction changes with the rotation direction of the spiral.

III. Principle

The magnetic torque T_m acting on the magnet in the external magnetic field is given by

$$T_m = m H \sin\theta \quad (1)$$

where m is the magnetic moment of the magnet, H is the amplitude of the magnetic field, and θ is the angle between m and H.

The torque required to rotate the mechanism with angular velocity ω ($= 2\pi f$) is given by

$$T_f = D\omega + EL/\omega \,. \quad (2)$$

The first term $D\omega$ and the second one EL/ω are the torque for the magnet and the spiral, respectively. Here D is the rotational damping coefficient of the magnet and E is the rate of working against the fluid per unit length of the spiral. The

Manuscript received February 26, 1996
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driving condition is therefore

$$T_m > T_f. \quad (3)$$

When the spiral rotates, the propulsive force is produced by the fact that the resistive force in the direction normal to the wire is larger than that in the tangential direction[2]. If the hydrodynamics of the proposed mechanism is the same as that of a bacterial flagellum, we can calculate the swimming velocity by using Lighthill's theory[3], in which spiral flagellar motions were analyzed based upon Stoke's equation of low–Reynolds–number flow. According to this theory, the swimming velocity U_0 in the ideal case where the drag on the magnet is negligible can be expressed by

$$U_0 = c\,\omega = 2\pi c f \quad (4)$$

where the coefficient c is determined by three parameters: λ, $2b$ and $2a$. Actually, the drag on the magnet causes the swimming velocity to decrease. The actual swimming velocity U can be expressed by

$$U = U_0 / (1 + A\psi / L) \quad (5)$$

where $(1+A\psi/L)$ is the velocity reduction factor. Here ψ is the nondimensional coefficient determined by λ, $2b$ $2a$, and L, and A is the radius of a sphere with the same drag as the magnet.

IV. Results and Discussion

Taking account of the cm–size of the mechanism, we used silicone oil with kinematic viscosity of 10 St and 100 St instead of water with 0.01 St, so that we could test swimming at $Re < 1$. The mechanism was placed in a test tube with inside diameter of 15 mm, which was filled with silicone oil and was held in the horizontal position. The alternating magnetic field was applied by an external electromagnet. The revolution of the magnet was equal to the excitation frequency.

The relation between the swimming velocity and the excitation frequency was examined first. Fig.2 shows the excitation frequency dependence of the swimming velocity for $\lambda = 3$ mm, $2b = 1$ mm, and $L = 21.7$ mm. The sign of the velocity means the swimming direction: in case of a plus sign it swam to the left–hand direction in Fig.1. Swimming was observed in the frequency range 10–33 Hz for 10 St and 2–5 Hz for 100 St. The Reynolds numbers Re obtained were below 1. From the hydrodynamic point of view, this successful swimming in the large–viscous fluid shows that this spiral–type mechanism is basically acceptable to the swimming microrobot with $Re < 1$.

The measured velocity increased in proportion to the excitation frequency. Although the frequency range required to swim depended on the amplitude of the magnetic field and the kinematic viscosity, the increasing rate was constant independent of these factors. The solid lines, which describe the calculation result based on Lighthill's theory, supported this experimental result. Because the increasing rate (that is, the moving distance per rotation) corresponds to the velocity at a given excitation frequency, it is reasonable to evaluate the value as the swimming velocity. In the following discussion, we examined the effects of the shape parameters on the swimming velocity.

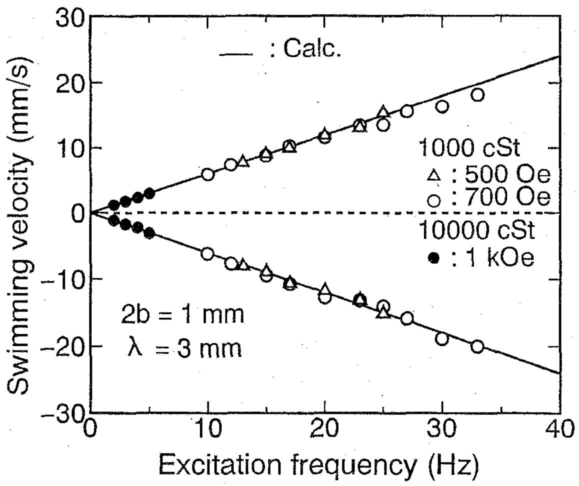

Fig.2 Excitation frequency dependence of the swimming velocity. Parameters: $\lambda = 3$ mm, $2b = 1$ mm, $L = 21.7$ mm.

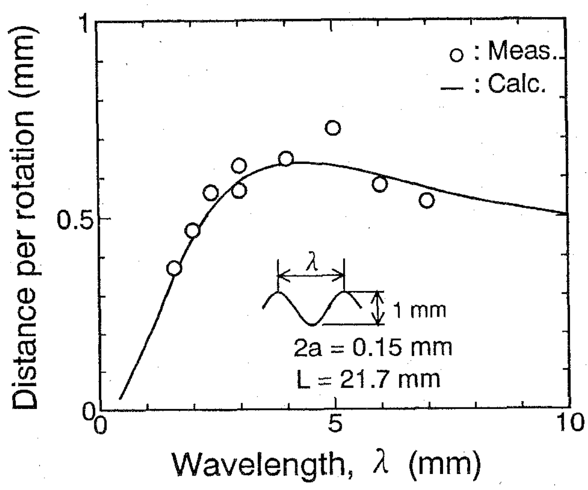

Fig.3 Moving distance per rotation as a function of the wavelength λ. Parameters: $2b = 1$ mm, $L = 21.7$ mm.

Fig.3 shows the swimming velocity for $2b$ = 1 mm and L = 21.7 mm as a function of the wavelength λ. The points and the solid line describe the experimental result and the calculated one, respectively. The experimental velocity increased with λ and reached a peak at λ = 5 mm. Afterwards further increase in λ caused the velocity to gradually decrease. The appearance of the peak velocity at a certain λ is to be expected from the hypothetical case where the swimming velocity is zero at λ = infinity and zero. We must note that the swimming velocity U is not proportional to the wave velocity V_w (= λf). In addition, there was a good agreement between the experiments and the calculation. Thus Lighthill's theory proved useful for predicting the swimming velocity.

Fig.4 shows the swimming velocity for λ =3 mm and L = 21.7 mm as a function of the diameter $2b$ of the spiral. The experimental velocity as described by the points increased rapidly with increasing $2b$. For $2b$ > 1.5 mm, however, the magnet could hardly rotate because the torque required to rotate the spiral increased largely. On the other hand, the calculation result up to $2b$ = 1.5 mm agreed approximately with the measured values but afterwards leveled off rapidly. These results show that a steep spiral with $2b$ beyond a certain value has the opposite effect on the swimming.

Finally, we examined the dependence of the swimming velocity on the total length L. Fig.5 shows the experimental and calculated velocity for λ = 3 mm and $2b$ = 1 mm as a function of L. The dotted line describes the ideal velocity in the case where the magnet is absent. The experimental swimming velocity as described by the points increased with increasing L. This is due to the fact that the propulsive force against the drag on the magnet increases as L increases. The calculation result described by the solid line agreed with the experiments and approached the ideal value gradually as L increased further.

We must now remark on the effect of the total length L on the power required for a given velocity. For extremely long spirals, the power EL for the spiral increases linearly with L, while the power $D\omega^2$ for the magnet is nearly constant. On the other hand, for short spirals in the range L < 25 mm, the mechanism must rotate faster as L decreases, which causes the power $D\omega^2$ for the magnet to increase rapidly. This suggests that there may be an optimum total length for minimizing the total power consumption. This point needs further consideration.

V. Conclusions

We proposed a spiral-type swimming mechanism for microrobots in water and fabricated a cm-size model. It was remotely operated by an external magnetic field and could successfully swim at low Reynolds number in a high-viscosity silicone oil. This result indicates that the mechanism proposed is suitable for swimming in a microworld. The swimming velocity increased linearly with excitation frequency and depended on the shape of the spiral. In addition, the experimental velocity agreed with the calculation result based on Lighthill's theory.

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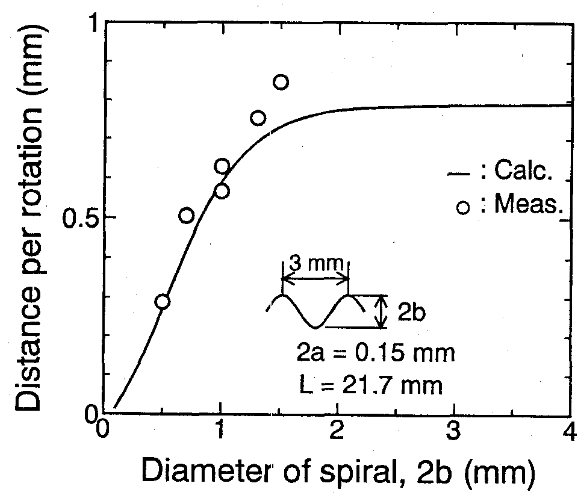

Fig.4 Moving distance per rotation as a function of the radius $2b$ of the spiral. Parameters: λ = 3 mm, L = 21.7 mm.

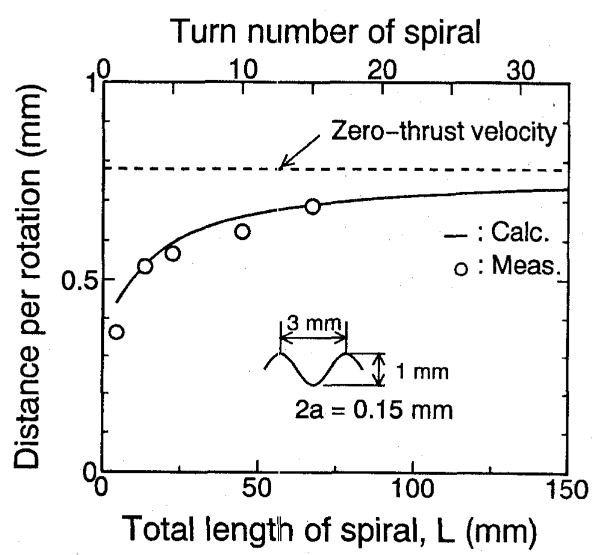

Fig.5 Moving distance per rotation as a function of the total length L of the spiral. Parameters: λ = 3 mm, $2b$ = 1 mm, L = 21.7 mm.