東北大学機関リポジトリ
TOUR
Tohoku University Repository

Effect of machine shape on swimming properties of the spiral-type magnetic micro-machine

著者	石山　和志
journal or publication title	IEEE Transactions on Magnetics
volume	35
number	5
page range	3688-3690
year	1999
URL	http://hdl.handle.net/10097/47767

doi: 10.1109/20.800632

Effect of Machine Shape on Swimming Properties of the Spiral-Type Magnetic Micro-Machine

M. Sendoh, N. Ajiro, K. Ishiyama, M. Inoue* and K. I. Arai
Res. Inst. of Elec. Comm., Tohoku Univ., 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan

T. Hayase
Inst. of Fluid Science, Tohoku Univ., 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan

J. Akedo
Mech. Eng. Lab., MITI, 1-2 Namiki, Tsukuba, Ibaraki 305-0044, Japan

Abstract—**Effect of a machine shape on swimming properties of the spiral-type magnetic micro-machine was examined by using a finite volume method. The optimum design of the blade shape was obtained by using the results of the simulation. According to the optimum design, the micro-machine was fabricated by a stereolithography. The swimming properties of the machine were agreed well with the analyzed results.**

Index Terms—**micro-machine, spiral blade, finite volume method, stereolithography.**

I. Introduction

Magnetic micro-machines are characterized by their wireless operation. Therefore they are expected to be used for medical micro-robots. Several magnetic micro-machines were examined on their fundamental properties [1]-[4]. In these machines, the spiral shaped swimming machine is most suitable for the medical micro-robots, because most parts of body components are liquid such as blood.

In our previous studies, swimming properties of the spiral type magnetic micro-machines were investigated [5]. In the studies, we demonstrated that the micro-machines could swim in liquids of various viscosity (1.4 to 1000 mm^2/s) or in a soft jelly. However, the swimming properties were varied with changing the condition of environments. This suggests there was an optimal structure of micro-machines depending on the swimming environments.

In this study, effects of the machine shape on the swimming properties of the spiral-type micro-machines were examined by means of the two-dimensional finite volume method. As a result, a guideline for designing the spiral blade was obtained. On the basis of the guideline, a spiral-type magnetic micro-machine was fabricated using the stereo-lithography.

II. Analysis of the Micro-Machine

A. Spiral-type Magnetic Micro-Machine

A schematic view of the spiral-type magnetic micro-machine is shown in Fig. 1. This micro-machine was composed of two cylindrical tiny magnets which were bonded at the both ends of the body. Onto the body, a spiral shape that is called "spiral blade" in this paper was structured.

By applying a rotating magnetic field, the micro-machine rotates synchronized to the external field. This rotation generates forward and backward thrust depending on the direction of rotation. In general, there is a boundary layer around the swimming machine as shown in Fig. 2. Within the boundary layer, the fluid is affected by the movement of the machine.

B. Simplified Model

Fig. 3 shows a simplified model used in this analysis. It made assumption that the micro-machine had infinite length in the direction of z-axis. R_2 was the thickness of the boundary layer. In order to simulate the swimming and rotating of the machine, cylindrical co-ordinates which were moving and rotating with machine, were used.

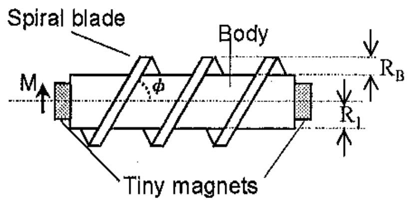

Fig. 1. Schematic view of spiral-type magnetic micro-machine.

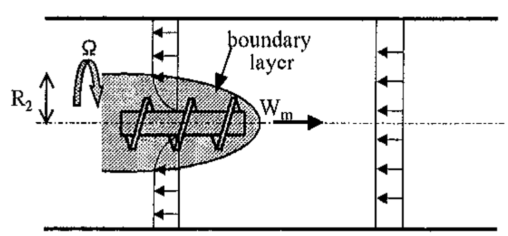

Fig. 2. Flow field around swimming micro-machine.

Manuscript received May 28, 1999.
M. Sendoh, 81-22-217-5488, fax 81-22-217-5489, sendoh@riec.tohoku.ac.jp,
This study was supported by the Promotion of Fundamental Studies in Health Science of the Organization for Pharmaceutical Safety and Research of Japan.
* Present address: Dept. of Electrical & Electronic Engng., Toyohashi University of Technology, Toyohashi, Aichi 441-8580, Japan.

0018-9464/99$10.00 © 1999 IEEE

Authorized licensed use limited to: TOHOKU UNIVERSITY. Downloaded on March 07,2010 at 20:22:07 EST from IEEE Xplore. Restrictions apply.

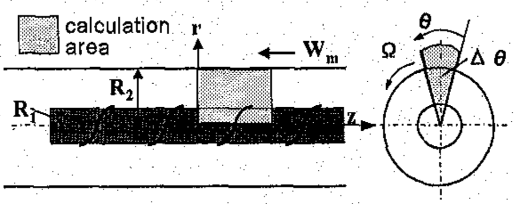

Fig. 3. Simplified model used in the analysis.

C. Calculation Method

Motion of incompressible viscosity fluid is described by the equation of Navier-Stokes and the equation of continuity. By using the finite volume method, these fundamental equations were solved under the no-slip condition [6]. Swimming properties were analyzed as follows [5] ; Using solved distribution of fluid velocity, drag and load torque, which were ascribable to the viscous stress on the machine surface, were calculated. Thrust and load torque, which were ascribable to the pressure difference between front and back of spiral blade, were calculated. The effect of two ends of the machine was considered as a drag of a disk with same diameter as the machine. Swimming velocity was analyzed as a point that the thrust of the machine was equal to the drag.

Effect of the blade height R_B and the blade angle ϕ (shown in Fig. 1) on the fluid dynamic efficiency ε was analyzed. ε was defined as the following equation (1).

$$\varepsilon = \frac{\text{Thrust} \times \text{Velocity}}{\text{Thrust} \times \text{Velocity} + \text{Load torque} \times \text{Angular speed}} \quad (1)$$

In these calculations, the thickness of the spiral blade and R_1 were constant values of 0.15 mm and 0.6 mm respectively.

III. Results and Discussion

A. Blade Height

To design the height of the spiral blade, the blade height dependence of the efficiency ε and the load torque was examined. The calculated efficiency is shown in Fig. 4. In every viscosity of the fluid, the efficiency increased by increasing the blade height and it has a peak value at R_B/R_1 = 2~3. This result showed the optimum blade height is R_B/R_1 = 2~3.

However the micro-machine with a larger blade height is difficult to swim. The calculated result of the relation between the blade height and the load torque is shown in Fig. 5. The load torque increased by increasing the blade height. This means the machine with a large blade height required large torque for rotating because of increasing of the surface viscous friction. Since a step out frequency of the machine was decided at the point of the load torque equals to the applied torque produced by the magnet and the external rotating field [3], the step out frequency should be lower by increasing R_B/R_1.

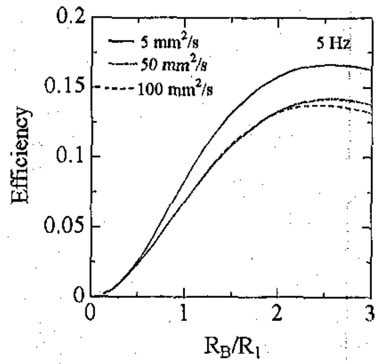

Fig. 4. Relationship between efficiency and blade height.

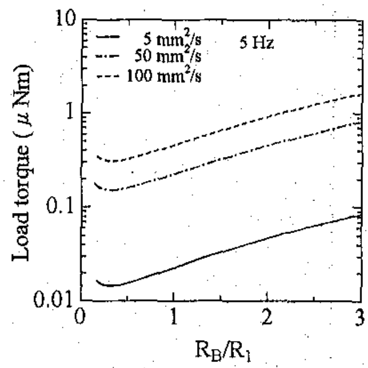

Fig. 5. Relationship between load torque and blade height.

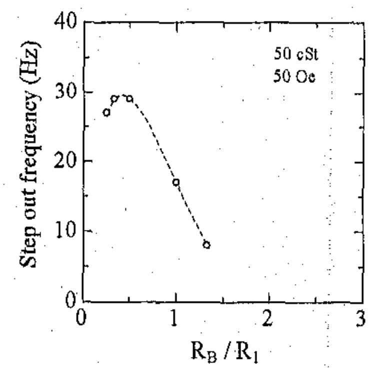

Fig. 6. Step out frequency versus blade height (experimented).

The experimental result of the relation between the blade height and the step out frequency is shown in Fig. 6. In this experiment, a wounded wire was used as the spiral blade. The step out frequency decreased with increasing the blade height. This result agrees with the calculated results. In addition, the point of R_B/R_1 that the calculated load torque is minimum agreed with the point that the step out frequency is maximum.

To obtain the micro-machine with high efficiency, the height of the spiral blade should be large within R_B/R_1 = 3. On the other hand, a higher blade makes the step out frequency lower and the maximum velocity smaller, because the velocity of the machine is maximum at just below the step out frequency. Therefore there is an optimum blade height between R_B/R_1 = 0.25 and 3, which depends on the

Authorized licensed use limited to: TOHOKU UNIVERSITY. Downloaded on March 07,2010 at 20:22:07 EST from IEEE Xplore. Restrictions apply.

magnetization of the magnet attached on the micro-machine, the magnitude of the external rotating field, and the viscosity of the fluid.

B. Blade Angle

To discuss about the design of the blade angle, the dependence of ε and the load torque on the blade angle was examined. Three blade angles of 30, 45, and 60 degree were chosen for the calculation.

Fig. 7 shows the efficiency and the load torque depending on the blade angle. From these figures the micro-machine with the 45 degree blade had the highest efficiency and the smallest load torque. This result corresponds to the previous result by the simple calculation[7].

According to these results, the optimum blade angle of the micro-machine is 45 degree because the blade angle makes the efficiency high and the load torque low.

IV. Prototype by Stereolithography

Based on the results before, a micro-machine with the optimum design was fabricated by the stereolithography. A photograph of the machine is shown in Fig. 8. The body was made by UV cured resin. Two cylindrical SmFeN magnets with diameter 1.2 mm and thickness 0.55 mm were bonded at the both ends of the body. Radius of the body (R_1) was 0.6 mm. The blade angle of the machine was 45 degree. In order to reduce the machine's load torque, the blade height was designed as 0.5 mm ($R_B/R_1 \fallingdotseq 0.33$).

The dependence of the swimming velocity of the micro-machine on the driving frequency is shown in Fig. 9. In this figure, the solid line means a computational result. The experimental result is plotted by an open circle. The calculated result agreed with the experimental one in lower frequency than the step out, even though the surface of the micro-machine made by stereolithography is not smooth. This suggests that the stereolithography is useful for the fabrication of the spiral-type micro-machines type of any.

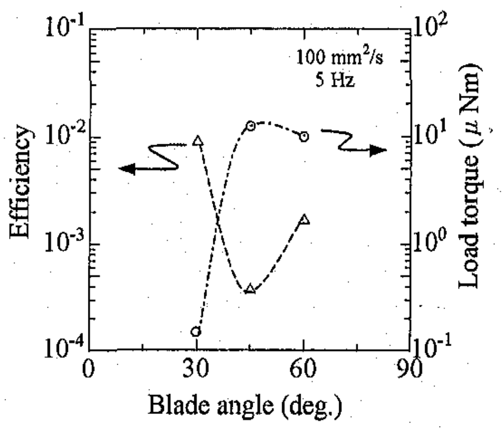

Fig. 7. Relationship between efficiency and blade angle.

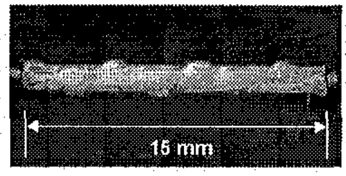

Fig. 8. Photograph of the micro-machine fabricated by stereolithography.

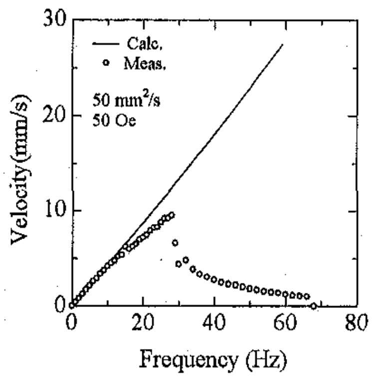

Fig. 9. Swimming velocity as a function of rotation frequency.

V. Conclusion

Effect of the machine shape on the swimming properties of the spiral-type magnetic micro-machine was examined by the finite volume method. A guideline for designing the spiral blade was obtained ; Blade height - There is an optimum blade height between $R_B/R_1 = 0.25$ and 3, within the micro-machine can be driven. Blade angle - Angle of the spiral blade should be designed to be 45 degree.

Based on this guideline of design, a micro-machine was fabricated applying the stereolithography. The calculated swimming properties of the micro-machine agreed with the experimental results. Using the stereolithography, any type of spiral-type magnetic micro-machine can be obtained under the simulated optimum design.

References

[1] T. Honda, K. I. Arai, and M. Yamaguchi, "Fabrication of magnetostrictive actuators using rare-earth (Tb, Sm)-Fe thin films", *J. Appl. Phys.*, vol. 76, No.10, pp. 6994-6999, November 1994.

[2] K. Shimasaki, M. Inoue, K. I. Arai, and T. Honda, "A theory for analyzing the flap motion of wings of small flying elements driven by a magnetic torque", *IEEE Trans. Magn.*, Vol. 34, No. 4, pp. 2096-2098, July 1998.

[3] M. Inoue, M. Sendoh, K. Ishiyama, K. Shimasaki, and K. I. Arai, "Swimming properties of magnetic micro-machine driven by a rotating magnetic field for use in medical micro-robots", *J. Appl. Phys.*, in press.

[4] A. M. Lavie, "The swimming of the POD : Theoretical analysis and experimental results", *IEEE Trans. Magn.*, Vol. 6, pp. 365-367, 1970.

[5] M. Sendoh, N. Ajiro, K. Ishiyama, M. Inoue, K. I. Arai, and T. Hayase, "Two-Dimensional Analysis of Properties of Magnetic Micro-Machines by Means of the Finite Volume Method", *J. Mag. Soc. Jpn.*, Vol. 23, pp.1665-1668, 1999 (in Japanese).

[6] S. V. Patankar, *Numerical heat transfer and fluid flow.* Hemisphere, Washington, DC/New York, 1980.

[7] T. Honda, K. I. Arai, and K. Ishiyama, "Micro Swimming Mechanisms Propelled by External Magnetic Field", *IEEE Trans. Magn.*, Vol. 32, pp. 5085-5087, September 1996.

Authorized licensed use limited to: TOHOKU UNIVERSITY. Downloaded on March 07,2010 at 20:22:07 EST from IEEE Xplore. Restrictions apply.