A Micro-Flight Mechanism with Rotational Wings

Norihisa MIKI and Isao SHIMOYAMA
Mechano-Informatics, University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
miki@leopard.t.u-tokyo.ac.jp

Abstract

A flight mechanism with 2 mm long micro-rotational wings has been designed and fabricated. The rotational wings are made of cobalt-nickel alloy and rotate in an alternating magnetic field. The flight mechanism is composed of the rotational wings, non-rotational body and disk. The wings and the disk are attached to the glass rod and rotate together. As the rotating frequency increases, the wings and the disk move up and the disk pushes the body upwards, and then the whole structures take off. The characteristics of the rotational wings are investigated. A scale effect is found; the characteristics of the rotational wings get better as the wing length decreases. It is considered to be caused by the wing-longitudinal flow, which is often ignored in high Reynolds number flow. The non-rotational body has soft magnetic films. Due to the magnetic anisotropic torque exerted on the films, the body can maintain its attitude stable passively. The flight mechanism that weighs 1.6 mg succeeded in taking-off at 438 Hz keeping the attitude of the body stable. The magnetic torque between the external magnetic field and the wings must be larger than the torque from the air and the friction in order to keep the wings rotating. The relationship between the required magnetic field and the rotating frequency is investigated.

Introduction

Micro-rotational wings that gain thrust by rotating magnetic wings in an alternating magnetic field was proposed and fabricated [1]. The wings are composed of electroplated cobalt-nickel alloy wings and a glass rod that works as the axis of rotation. They rotate in a glass tube in an alternating magnetic field. 0.9 mm long wings that weigh 165 μg succeeded in taking off at a rotating frequency of 570 Hz. But the attitude cannot be maintained, after the wings take off from the guide. One possible reason could be because the whole structures rotate.

In this paper the flight mechanism with the rotational wings and a non-rotational part is proposed. The schematic view of the flight mechanism is shown in Fig. 1. It is composed of the rotational wings, silicon body and disk. The wings and the disk are made of electroplated cobalt-nickel alloy (CoNi) and attached to the glass rod that works as the axis of rotation. They rotate together in an alternating magnetic field. As the rotating frequency increases, the wings and the disk move up and the disk pushes the silicon body upwards. When the thrust generated by the rotational wings overcomes the weight of the mechanism, it takes off.

In order to keep the attitude of the body stable, soft magnetic films are attached on the body as shown in Fig. 1. When the magnetic field is applied in the x axis direction, the magnetic anisotropic torque exerted on the magnetic film prevents the silicon body from rotating around the y and z axis due to their shapes. Without the films, the silicon body rotates as the wings are rotating because of the friction between the rotating glass rod, the CoNi disk and the silicon body. The flight mechanism that weighs 1.6 mg succeeded in taking-off at 438 Hz while the body keeps its attitude stable.

In previous work, a flapping mechanism using semiconductor surface machining technology was fabricated and analyzed [2], [3]. A small flying machine which was 3 cm long was fabricated and flew in an alternating magnetic field of more than 400 Oe and 12 Hz [4].

Characteristics of the rotational wings

The schematic view of the rotational micro-wings is shown in Fig. 2. The thrust T generated by the rotational wings can be calculated by integrating dT that is generated by the small segment of the wings. In this calculation, the influence from the neighbor segments is ignored, which is often hypothesized in conventional fluid dynamics. The thrust generated by the rotational wings of length R and rotating at a frequency of f can be expressed as

$$T = \frac{2}{3}\pi^2 \rho b c f^2 R^3 (C_l + \phi C_d) \quad , \qquad (1)$$

where ρ is the density of the air, b is the number of the wings, c is the chord length of the wing, ϕ is the induced

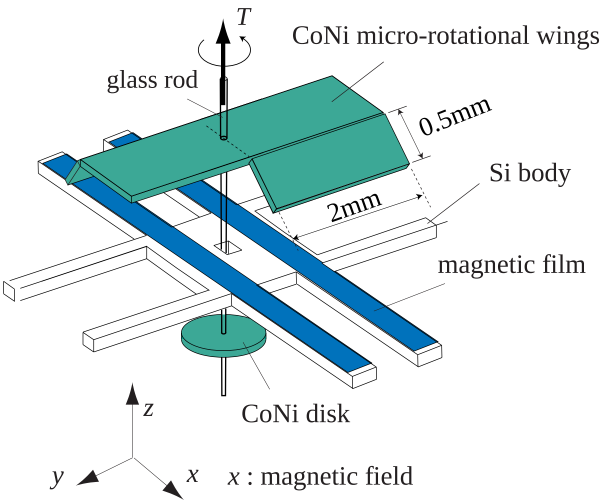


Fig. 1. Schematic view of the rotational micro-wings.

angle, and C_l and C_d are the coefficients of lift and drag respectively. Both of the coefficients are hypothesized to be constant with respect to R.

The 900 µm long micro-wings which weigh 165 µg succeeded in flying up along the guide at a rotating frequency of 570 Hz. When the rotational micro-wings start to fly up, the thrust generated by rotating wings can be regarded as equal to the weight of the wings.

The value of ($C_l + \phi C_d$) in Eq.(1) is investigated with respect to the wing length. It is defined as C_{rw}. When its value is known experimentally, the thrust generated by the rotational wings can be calculated by Eq.(1). Hence C_{rw} can be regarded as the non-dimensional number that represents the characteristic of the rotational wings. C_{rw} can be calculated by substituting the weight of the wings for T and the take-off frequency for f. The results are shown in Fig. 3.

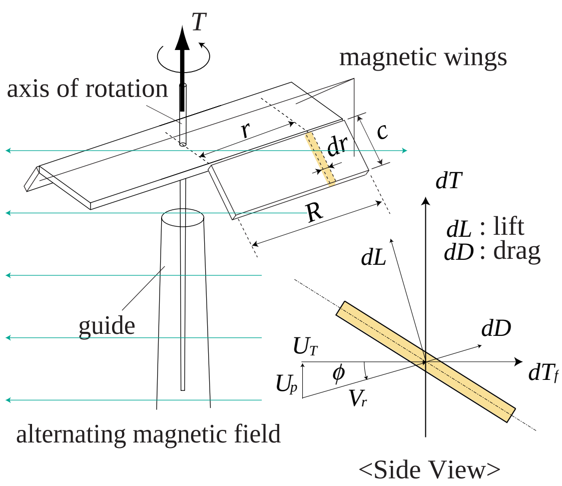


Fig. 2. Schematic view of the rotational wings.

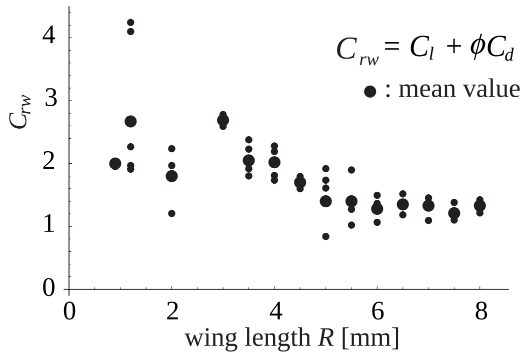


Fig. 3. C_{rw} vs. wing length R.

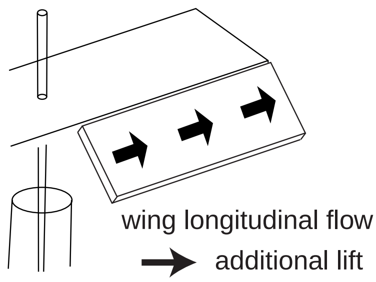


Fig. 4. Wing longitudinal flow.

C_{rw} increases as the wing length decreases from 8 mm to 3 mm. The reason for this scale effect is considered as follows: as the wings get smaller, the Reynolds number decreases, that is, the influence of the viscosity increases. Therefore the influence of the wing-longitudinal flow as shown in Fig .4 cannot be ignored. The flow generates some vortices and an additional lift, which is observed in the flight of insects [5].

A sharpened glass rod is used as the axis of rotation for less than 2 mm long micro-wings. C_{rw} of micro-wings is smaller than expected due to the electrostatic force between the glass rod and the outer glass tube. From the result C_{rw} is found to be around 2.

Flight mechanism

Large-sized models

A flight mechanism shown in Fig. 5 is designed and fabricated as a large-sized model. The flight mechanism consists of iron rotational wings, glass tube, soft magnetic body and polyimide legs. The glass tube is attached to the body. The edge of the tiny pin is bent and it transmits the thrust from the rotational wings to the whole structure.

When the magnetization slides away from the easy magnetized axis of the magnetic materials, magnetic anisotropic torque is generated. The easy magnetized axis of the body is in the x axis direction due to its shape.

When the magnetic field alternates in the x axis direction, the magnetic anisotropy torque acting on the soft magnetic body prevents the mechanism from rolling around the y and z axis.

The legs contribute to the stability around the x axis. The flight mechanism with 7 mm long rotational wings succeeded in taking-off at a rotating frequency of 191 Hz. The coil generating an alternating magnetic field has a spatial difference in the strength of the magnetic field. As the magnetic field along the wall is stronger than that in the center of the coil, the flight mechanism is attracted towards the wall, rolling around the x axis, after taking off. The guides shown in Fig. 5 prevent the excess rolling of the mechanism.

From the experiments, it is proved that the magnetic anisotropic torque is effective in controlling the attitude around the y and z axis. The magnetic anisotropic torque cancels the friction between the tiny pin and the glass tube around the z axis.

Micro-flight mechanism

The micro-flight mechanism which is about one-tenth in size of the large-sized model is designed and fabricated using MEMS technology. The schematic diagram is shown in Fig. 1.

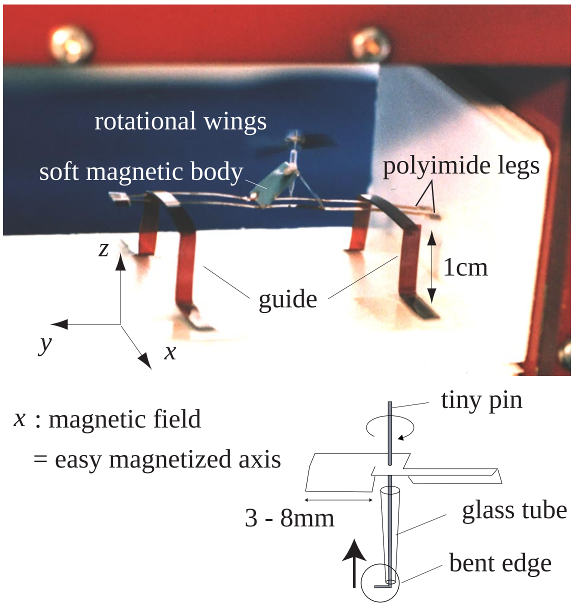


Fig. 5. A photo of the large-sized model of the flight mechanism.

SiO_2, Cr and cobalt-nickel alloy layers are sputtered on a silicon substrate. Cobalt-nickel alloy is electroplated as shown in Fig. 6, which will become the wings and the disk. Cr is the contact metal and CoNi is the seed layer for the electroplating process, while SiO_2 is the sacrificial layer.

Thick structures can be fabricated with less residual stress by electroplating than sputtering. Another merit of electroplating is that the etching of the structure is not required which could cause the problem of under-etching that is more serious with thicker structures.

The silicon body has magnetic films on the top in order to use the magnetic anisotropic torque. Experiments were conducted on three different materials deposited on the top of the body; (I) sputtered nickel, (II) electroplated nickel and (III) amorphous film made of $Fe_{67}Co_{18}B_{14}Si$. Their lengths are 3 mm and the widths are 200 µm. The sputtered nickel is 1 µm thick. The electroplated nickel is 4.5, 9.0 and 13.5 µm thick. The amorphous film is 25 µm thick. The silicon body is fabricated by anisotropic etching by TMAH. For types (I) and (II), nickel is sputtered and electroplated, respectively, before the anisotropic etching. For type (III), the amorphous film is attached on the body after the etching. The mass of type (I) and (II) silicon body is larger than type (III) because of silicon under the sputtered and electroplated nickel. The SEM photos of (a) the top view and (b) the bottom view of the silicon body with electroplated nickel are shown in Fig. 7.

The fabrication process after removing the sacrificial layer is shown in Fig. 8. The supporting beams prevent the wings from attaching to the substrate. Wings are bent to generate angles of attack. The structures are raised up orthogonally to sandwich the silicon body. A sharpened glass rod 80 µm in diameter is inserted through the wings, body and disk, which works as the axis of rotation. The wings and the disk are attached to the glass rod with bonding paste.

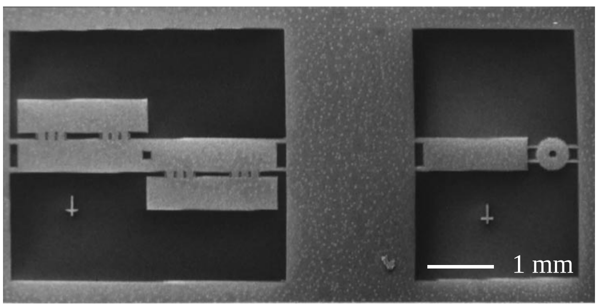
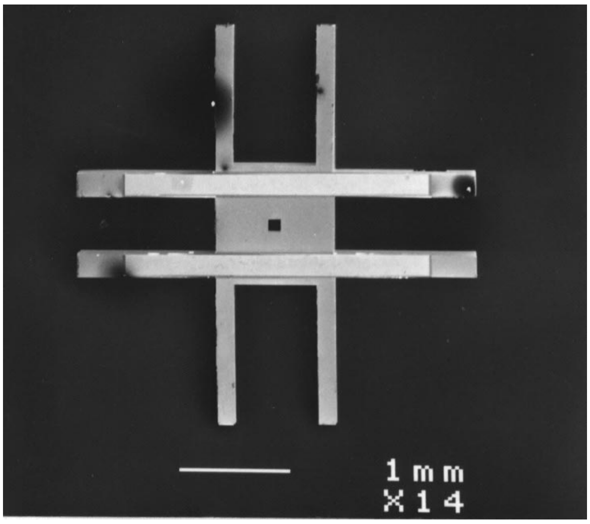
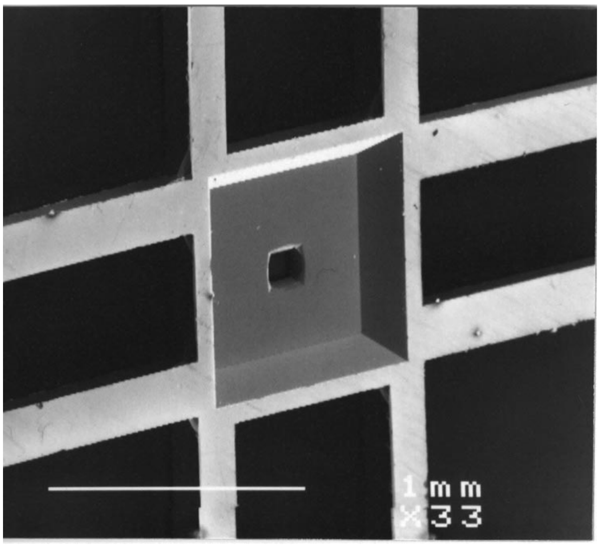


Fig. 6. Electroplated CoNi.



(a)



(b)

Fig. 7. Photos of the silicon body (a) top view, (b) bottom view.

Experimental

When the magnetization slides away from the easy magnetized axis at an angle of α, the anisotropic torque T_a is expressed as,

$$T_a = -V_{mag} K_a \sin 2\alpha \quad , \tag{2}$$

where V_{mag} is the volume of the magnetic material and K_a is the magnetic anisotropy constant which depends on the shape, stress, crystalline and other factors. For this study, only the shape anisotropy is taken into consideration. For the magnetic films as shown in Fig. 1, the easy magnetized axis is in the x axis direction. K_a around the z axis is expressed as,

$$K_a = \frac{1}{2\mu_0}(N_y - N_x) I_s^{\,2} \, , \tag{3}$$

where N_y and N_x are the demagnetizing factors in the y axis and x axis direction, respectively. I_s is the saturated magnetic flux density of the material. I_s of nickel and $Fe_{67}Co_{18}B_{14}Si$ are 0.61 T and 1.8 T. Table 1. shows the volume of $V_{mag}\,K_a$ in Eq.(2), where N_y and N_x are evaluated assuming that the magnetic films are oblate spheroids.

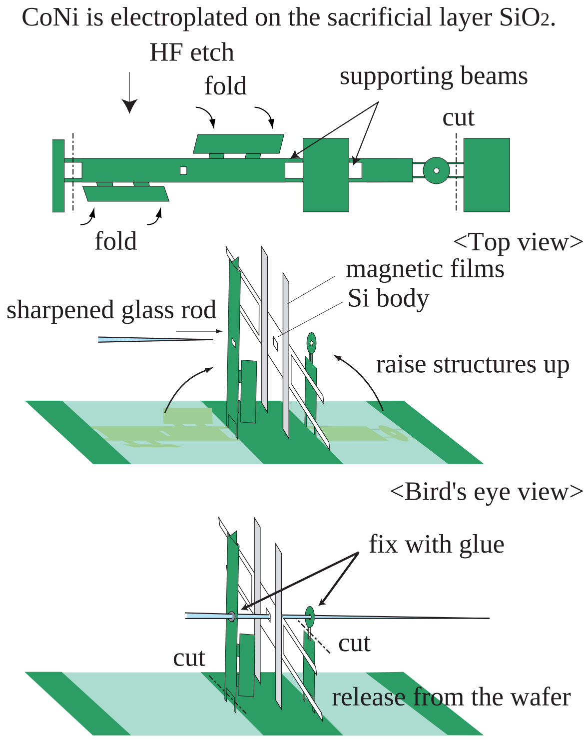
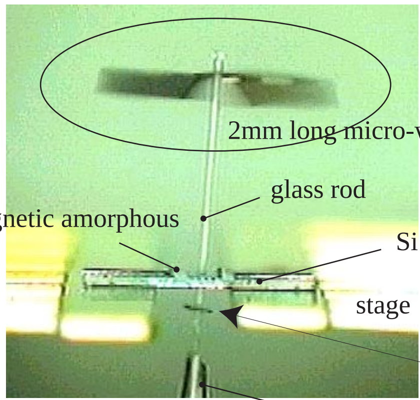


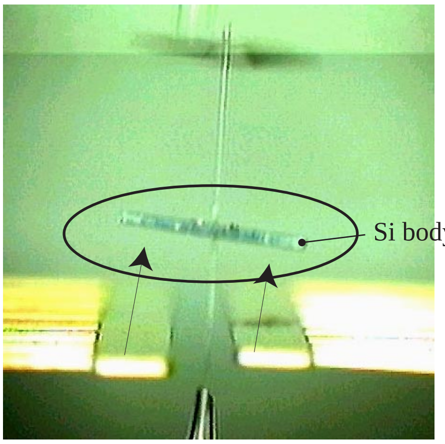
Fig. 8. A fabrication process.

Table 1. Magnetic anisotropy constants.

	(I)	(II)			(III)
thickness [µm]	1.0	4.5	9.0	13.5	25
$V_{mag}\,K_a$ [pN m]	0.36	6.0	18	54	1300
attitude control	fail	-	-	-	suc-ceed



(a)



(b)

Fig. 9. Photos of the micro-flight mechanism.

The scene of the experiments with type (III) silicon body is shown in Fig. 9 (a). The silicon body is put on the stage. The glass rod is inserted into a glass tube that works as a guide. There is a problem in stabilizing the rotation. Further study on the stabilization of the rotation has to be investigated.

As the wings start to rotate, friction is generated between the glass rod and the body. At a rotating frequency of 240 Hz, the wings and the disk move up. The disk starts to push the silicon body upwards generating friction between the disk and the body. If the magnetic anisotropic torque exerted on the silicon body is not sufficient, the body also rotates because of the friction. The experimental result shows that type (I) body rotates while the wings are rotating. On the other hand, type (III) does not rotate, meaning that it succeeds in controlling the attitude passively. In the experiments with type (II) body, the stability of the attitude depends on the accuracy of the fabrication, which indicates friction depends on the condition of the contact between the body and the disk.
The flight mechanism with type (III) silicon body 1.6 mg in weight succeeded in taking-off at 438 Hz as shown in Fig. 9 (b). Note that the silicon body doesn't rotate while the wings are rotating.

These experiments indicate that when V_{mag} K_a in Eq.(2) is over 1000, the magnetic films can generate sufficient magnetic anisotropic torque for attitude control. V_{mag} K_a varies with different shapes and materials.

C_{rw} of the rotational wings of the flight mechanism is found to be 1.3, which is much lower than expected. This is caused by the vibration of the glass rod, the electrostatic force between the glass rod and the guide and other factors. C_{rw} can be improved with the accuracy of the fabrication.

The flight mechanism 2.2 mg in weight with the silicon body with 4.5 µm thick electroplated nickel failed to take off because the wings cannot rotate at a sufficient frequency to generate the thrust to overcome the weight of the mechanism. As the rotating frequency increases, the disk pushes the body with stronger force and the friction between them increases. The torque from the air also increases. Hence in order to keep the wings rotating at a higher frequency, stronger magnetic field is required.

In order to investigate the relationship between the frequency and the required magnetic field to maintain the rotation, experiments were conducted on the flight mechanism with the body fixed by glass rods as shown in Fig. 10. Figure 11 shows the result. The maximum magnetic field of the coil is around 120 Gauss and the maximum frequency to maintain the rotation is around 450 Hz. The flight mechanism of lower weight and with less friction must be developed.

Conclusions

A micro-flight mechanism with magnetic rotational wings has been designed and fabricated. The characteristics of the rotational wings were investigated with respect to the non-dimensional number C_{rw}. As the wing length decreases, C_{rw} increases, which is one of the scale effects. This scale effect is considered to be caused by the wing longitudinal flow. From the experiments, C_{rw} can be assumed to be 2.

The flight mechanism is composed of the rotational wings, non-rotational silicon body and disk. The silicon body has magnetic films which exerts magnetic anisotropic torque. Passive control using the anisotropic torque was successfully achieved. From the experiments, it is found that the value of V_{mag} K_a of over 1000 is desirable which varies with different shapes and different materials of the magnetic films.

The micro-flight mechanism with 2 mm long CoNi rotational wings that weighs 1.6 mg succeeds in taking-

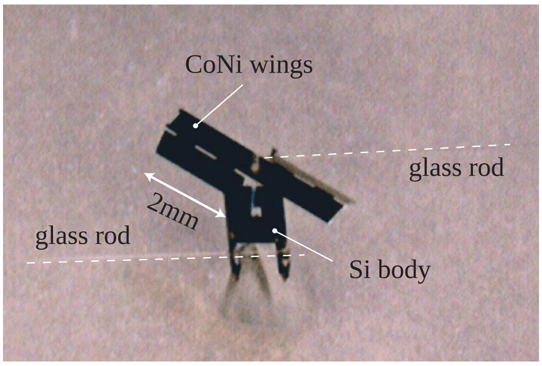


Fig. 10. A fixed body

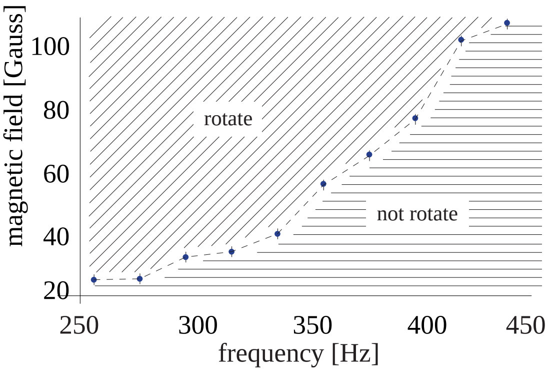


Fig. 11. Frequency vs. required magnetic field.

off at 438 Hz with the silicon body keeping its attitude stable. The wings cannot maintain their rotation at over 450 Hz due to the friction between the disk and the body. At 450 Hz, the rotational wings 2mm long and 0.5 mm in chord length generates 2.5 mgf when C_{rw} is assumed to be 2. But C_{rw} of the flight mechanism was found to be 1.3 in the experiments. In order to realize the flight, the reduction of the weight, friction and vibration is necessary.

Acknowledgements

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