Design of Selectively Controllable Micro Actuators Powered by Remote Resonant Magnetic Fields

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Abstract. Micro actuators for tiny robots could lead to revolutionary advances in many cutting-edge applications (e.g. minimally invasive medicine). Many prototypes were hence developed, which were powered either by micro organism, by onboard mechatronic systems or by remote magnetic fields. This paper presents two evolving designs, aiming at fabricating micro actuators which can be selectively controlled by weak resonant magnetic fields. The core concept is to design a spring-mass structure to convert the vibrations of soft magnets into rotary outputs. The fabricated micro actuators could then drive propellers or revolute joints for locomotion or manipulation tasks. The proposed designs essentially directly harvest magnetic energy to perform mechanical work, avoiding complex system components from traditional motorized actuation units, such as windings, commutators, batteries, etc.

Keywords: Micro actuators, soft magnets, resonant magnetic fields, micro fabrication.

1 Introduction

Micro robots could find many potential applications in minimally invasive medicine, such as performing diagnosis and treatments in intracranial cavities and vascular systems [1, 2]. These visionary functions could not be realized unless micro actuators are integrated into micro robots for swimming through low-Reynolds-number regions [2, 3] and performing manipulation tasks. Both locomotion (such as intravascular swimming or crawling) and manipulation depend on properly integrated micro actuators. Actuation designs of many existing micro robots fall into one of the following categories:

- ✧ Engineered micro organisms (such as bacteria) were used to provide propelling actuation, as in [4-7]. Ensuring controllability and biological safety of such robots could be quite challenging.
- ✧ A standalone micro robot with an onboard power and a controller is also possible, such as the designs in [1, 8-10]. Fabrication complexity and difficulty might be a real obstacle when such a micro robot is further downsized.
- ✧ Strong magnetic fields could be used to drive micro robots. These micro robots made from magnetic materials could be dragged by a static magnetic gradient

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(e.g. the designs in [11-13]). Or a rotating or an oscillating magnetic field can be used to spin or swing a micro robot so that its helical or flexible tail can generate thrusts for swimming (e.g. the designs in [14, 15] [16-18]). However, individual control of a swarm of robots can be quite difficult.

✧ A weak oscillating magnetic field could be used to trigger a resonant vibration between a micro robot's mass blocks made from soft magnetic materials. Then the collision could be modulated to provide thrusts, as presented in [19-21]. Different resonant frequencies can be used to control different robots. However, the aforementioned designs need a frictional surface to operate, which puts practical limitations for the designs' practical applications.

Inspired by the results from the work as in [19-21], this paper presents two evolving designs as shown in Fig. 3 and Fig. 7, aiming at fabricating a micro actuator which can be selectively remotely controlled by weak resonant magnetic fields. With such micro actuators fabricated and equipped, micro robots might then be able to actively navigate around (swim or crawl) and perform manipulation tasks.

The main contribution of this paper is the proposal of fabricating micro actuators which essentially directly harvest magnetic energy in space to perform mechanical work. These actuators consist of mass-spring structures using properly arranged soft magnetic and non-magnetic materials. Success of the proposed idea could lead to the development of micro actuators which could be remotely controlled by weak oscillating magnetic fields under different frequencies. And such micro actuators would find wide applications in both minimally invasive medicine and other fields.

The paper is organized as follows. Section 2 presents the working principle of the design concepts. Section 3 presents the coil design for generating oscillating magnetic fields. Section 4 and Section 5 present the alpha design and the beta design, including design simulations and fabrication attempts. Conclusions and future work are summarized in Section 6.

2 The Design Concept

Working principle of the design concepts is shown in Fig. 1. Mass blocks made from soft magnetic materials are connected by a non-magnetic spring. When an external magnetic field is applied, the mass blocks made from soft magnetic materials are magnetized. An attraction force is hence generated between the blocks to compress the non-magnetic spring. When the external magnetic field is removed, magnetization of the blocks disappears and so does the attraction force. The compressed spring generates a repulsive force to push the blocks apart.

When the external magnetic field is switched on and off at a frequency that matches the resonant frequency of the mass-spring system, mechanical energy (kinetic energy of the blocks and elastic potential energy of the spring) will accumulate within the system. When the accumulated energy exceeds a threshold, a designed structural feature will allow the output of the energy via a collision or modulated friction.

Following this working principle, two conceptual designs are presented in later sections, aiming at producing a micro actuator which can be selectively remotely controlled by resonant magnetic fields. The designs essentially directly harvest magnetic energy to perform mechanical work, avoiding complex system components from traditional motorized actuation units, such as windings, commutators, batteries, etc. With such micro actuators fabricated and equipped, micro robots might then be capable of swimming or crawling around and performing manipulation tasks.

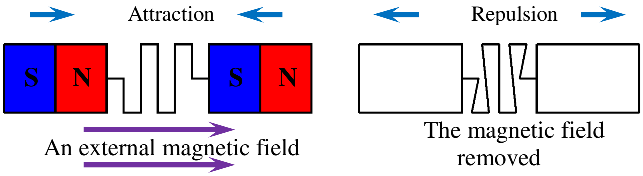

Fig. 1. Working principle of the design concept

3 The Coil Design

According to the working principle of the design concept, a fast switching magnetic field will be needed to actuate the micro actuators. This section presents the design of a coil system for such a magnetic field. Since the magnetic field will be primarily used to test the micro actuators that generate rotary outputs without moving around, the uniformity of the magnetic field is not much concerned. This work hence chose to apply a pair of Helmholtz coils due to its widely accepted effectiveness.

According to [20], a magnetic field with the magnetic flux density as weak as 2mT is capable of driving the micro robots with planar movements. 2mT is hence selected as the design goal of the coil system. Since the magnetic flux density matters the strength of the magnetization and hence affects how fast the harvested energy accumulates within an actuator, a slightly weaker or stronger magnetic field should be always capable of driving the actuators, as far as the principle works.

As shown in Fig. 2, a Maxon motor amplifier (LSC 30/2) working in its current mode was used to drive the pair of Helmholtz coils. Since the current output of the amplifier is limited to ±2A, the coils are assumed to have a 1.5A current while finalizing the coil parameters following the approach as in [22]. Each coil in the Helmholtz pair has a diameter of 30mm and 45 turns (distributed in 6 layers as 8-7-8-7-8-7 turns per layer). Distance between the center planes of the coils is also kept 30mm, as shown in Fig. 2-(b).

Referring to Fig. 2-(a), square-wave signals from the signal generator are connected to the V_{set+} and V_{set-} ports of the Maxon amplifier. Motor+ and Motor– ports of the Maxon amplifier are connected to the Helmholtz coils and a resistor serially. Voltage on the resistor is monitored by an oscilloscope to indicate the current flowing through the coils. P_{gain} and N_{max} knobs of the amplifier can be adjusted for the current to better follow the desired signal. Using this setup, an on/off current of 1.5A

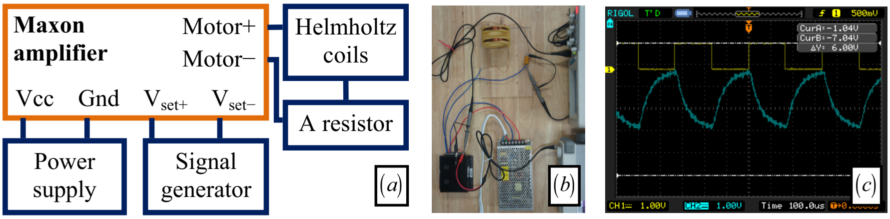

Fig. 2. The Helmholtz coils with the actuation circuit: (a) the schematic, (b) the actual system, and (c) wave form of the current in the Helmholtz coils following a 3.3KHz square-wave signal

can be driven to follow a square-wave signal with a frequency up to 3.3 KHz, as shown in Fig. 2-(c).

4 The Alpha Design

4.1 The Conceptual Structure

Following the aforementioned working principle, the alpha design is shown in Fig. 3. It consists of a base, an output rotor, two vibrators and two asymmetric planar springs. The vibrators are made from soft magnetic materials (electrically deposited nickel) and the springs are made from non-magnetic materials (electrically deposited copper). The nickel vibrators are sandwiched by the two copper springs.

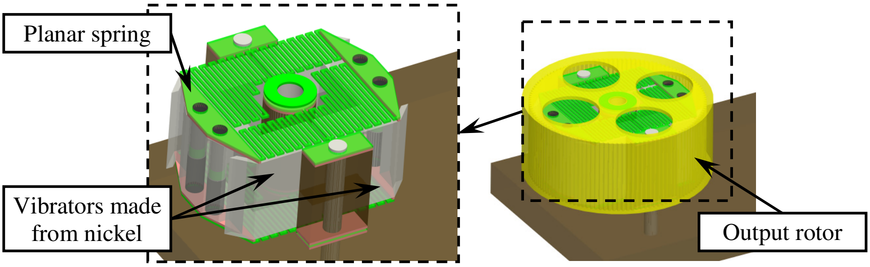

Fig. 3. The alpha design with a sandwiched spring-mass structure

When the spring-vibrator system is placed in an oscillating magnetic field (a fast switching on/off magnetic field), different resonant frequencies of the spring-vibrator system will lead to different vibration patterns. Making use of these different vibration patterns, the alpha design is expected to generate counterclockwise and clockwise rotary outputs when the magnetic field is switched on and off at different resonant frequencies.

Finite element simulations were then carried out to verify this conceptual structure.

4.2 Design Simulations

Back view of this alpha design is shown in Fig. 4-(a) for better indication of the geometrical dimensions of this design. The alpha design can be disassembled into i) the output rotor and ii) the sandwiched spring-mass structure.

- ✧ The output rotor has an outer diameter of 1 mm (1000 um).
- ✧ The Ni (nickel) vibrator blocks have a width of 600 um. The gap between the two Ni blocks is 20 um. An attraction force of about 1.2×10^{-6} N will be generated when the Ni blocks are magnetized in a magnetic field of 2 mT.
- ✧ Pointed corners (P_1, P_2, P_3 and P_4) are designed for the vibrators so that kinetic energy can be better transferred to the output rotor through collisions when the vibration amplitude becomes big enough under resonant frequencies.
- ✧ Width and layer thickness of the Cu spring are both 10 um. There are two holes with a diameter of 70um for relative positioning of the Cu spring and the Ni block.

Vibration patterns of the spring-mass structure under different resonant frequency were simulated in COMSOL.

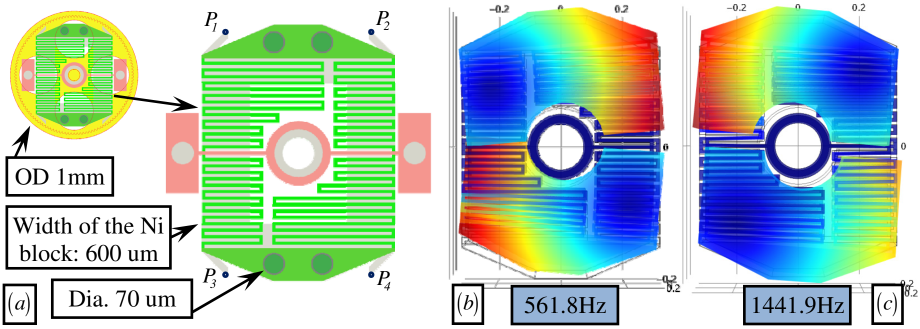

Fig. 4. Resonant vibrations of the alpha design: (a) geometrical dimensions, (b) the vibration pattern in an oscillating magnetic field at 561.8 Hz, and (c) the vibration pattern at 1441.9 Hz

As shown in Fig.4-(b), when the magnetic field is switched on/off at a resonant frequency of 561.8Hz, the nickel vibrator is oscillating in a rotary pattern with the center of motion located at the left side (indicated by the dark blue dot). When the vibration amplitude becomes bigger under this resonant excitation, the pointed corners P_1 and P_4 will hit the inner wall of the output rotor. A continuous counterclockwise rotation is then expected from such repeated collisions.

Similarly, at a higher resonant frequency of 1441.9Hz as shown in Fig. 4-(c), the nickel vibrator is oscillating with the center of motion located at the right side. At this higher frequency, the pointed corners P_2 and P_3 have bigger vibration amplitudes and they shall hit the inner wall of the output rotor. Such repeated collisions are then expected to generate continuous clockwise rotation outputs.

The gap between the pointed corners of the nickel vibrator and the inner wall of the output rotor is kept 6 to 10 um. At non-resonant frequencies of the spring-vibrator system, amplitudes of the vibrators will not be big enough to hit the inner wall of the output rotor. Hence no rotation outputs are expected when the external magnetic field is switched on/off at non-resonant frequencies.

Cavities can be included in the nickel vibrators to change the mass distribution. This will lead to changes in the resonant frequencies. Then different micro actuators could be designed to work under different excitation frequencies.

4.3 Fabrication and Assembling Attempts

It will be a challenging and costly process to fabricate the alpha design from Fig. 3 as one piece going through consecutive micro fabrication steps. In order to lower the fabrication costs, it was decided to fabricate the components of the alpha design separately and assemble the components. Some fabrication results are shown in Fig. 5.

- ✧ The output rotor and the rectangular spacer blocks as in the insets (a) and (b) were fabricated via lithography using photoresist SU-8 (UV LIGA). The output rotor has been produced with various inner diameters.
- ✧ The nickel vibrator shown in the inset (c) was produced by lithography followed by electrical deposit of nickel. The thickness is 360 um.
- ✧ The copper spring and copper spacer as in the insets (d) and (e) were produced using lithography followed by electrical deposit of copper. The thickness is 10 um.

Tolerances of these fabricated components are all within ±5 um. After picking components with fitting tolerances, it is possible to assemble these components to form the alpha design using a micro positioning device.

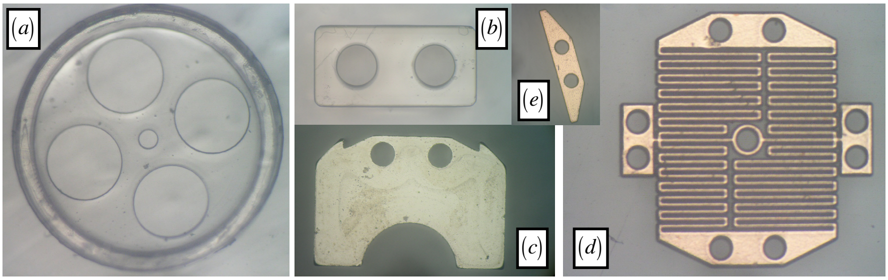

Fig. 5. Partial fabrication results of the alpha design

The proposed assembling process is shown in Fig. 6:

a) The connecting poles will be firstly inserted into the holes in the base; then the removable spacers (the blue ones) and the structural spacers (the pink ones) will then be placed;
b) The copper spring can now sit on top of the spacers; then another layer of the structural spacers (the pink ones) and the connecting pins (the blue ones) will be placed; glue droplets will be applied to bond the spring to the pins;
c) The rectangular block spacers (the brown ones) and the removable spacers (the blue ones) will be placed;

d) The nickel vibrator blocks will be placed on the connecting pins with another layer of the structural spacers (the pink ones); glue droplets will be applied again in the holes for the connecting pins;
e) The top spring can now be placed; and after the glue is set, the removable spacers (the blue ones) will be pulled out;
f) The output rotors will be assembled.

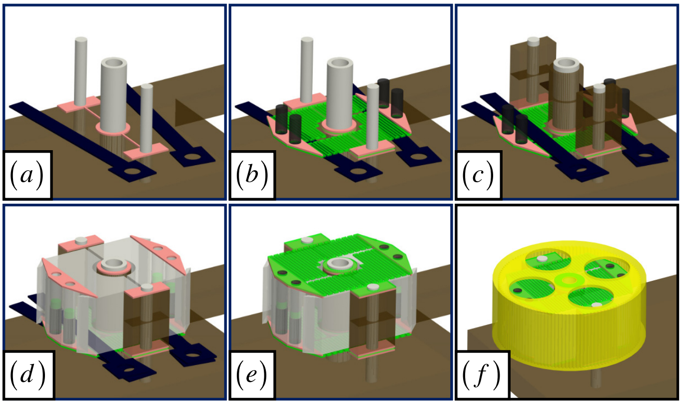

Fig. 6. Proposed assembling process of the alpha design

5 The Beta Design

It was planned to use a micro positioning device with a gripper to assemble the alpha design. Such suitable positioning devices are available from various suppliers (e.g. Thorlabs Inc.). However, a proper gripper was not identified. None of the home-made grippers using suctions, adhesives, or static electricity attractions could pick up and drop a component without affecting the components already in place. The alpha design was hence modified to form the beta design.

5.1 The Conceptual Structure

The beta design shown in Fig. 7 now has a layered spring-mass structure. It would be cheaper and easier to fabricate the layered spring-mass structure of the beta design than to fabricate the sandwiched structure of the alpha design as one piece

The beta design consists of i) a base, ii) an output rotor, and iii) a layered spring-mass structure. Similarly to the alpha design, the two nickel vibrators are expected to have various vibration modes under different resonant excitation frequencies to generate clockwise and counterclockwise rotations of the rotor.

A series of design simulations are presented in the next section to explain a minor revision of this design.

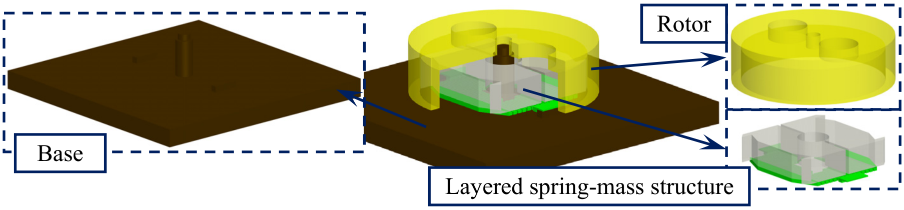

Fig. 7. The beta design with a layered spring-mass structure

5.2 Design Simulations

Vibrations of the layered spring-mass structure of the beta design are simulated in COMSOL to verify the existence of the desired vibration patterns. Geometrical parameters are listed as follows.

- ✧ The output rotor has an outer diameter of 1250 um.
- ✧ The nickel vibrator blocks have a width of 800 um and a thickness of 200 um. The gap between the two nickel blocks is 30 um.
- ✧ Width and layer thickness of the Cu spring are 10 um and 20 um respectively.

The simulated vibration patterns are presented in Fig.8. The patterns were exported to Matlab to plot the trajectories of the pointed corners. At an excitation frequency of 340 Hz, the vibration pattern is consistent with the design expectation: one side has considerably bigger amplitude to always trigger collisions on this side with the output rotor so as to generate a continuous rotary output. However at the second resonant frequency of 1797 Hz, the nickel vibrator has similar amplitudes at both sides. Continuous rotary output can hardly be expected since collisions on both sides would cancel out each other.

A series of simulations were carried out, trying to identify a beta design whose second resonant vibration mode meets the design requirement, by altering the mass distribution of the nickel vibrator and the layout of the spring. A proper spring-mass structure with such a desired second resonant vibration pattern was not identified.

A design compromise was made and the final beta design is shown in Fig. 9. Instead of having four pointed corners, the final design only features two pointed corners and only utilizes the first resonant vibration patterns.

The upper portion of the spring-mass structure has the first resonant frequency of 340 Hz, under which only the corner P_1 will collide with the rotor. The lower portion of the spring-mass structure has the first resonant frequency of 450 Hz, under which only the corner P_2 will collide with the rotor. Although the counterclockwise and clockwise rotations of the rotor could still be realized, efficiency of the final beta design could be relatively low. The reason is quite obvious: during resonant vibrations, only one vibrator mass (the upper one at 340 Hz or the lower one at 450 Hz) would transfer its kinetic energy to the rotor through collisions.

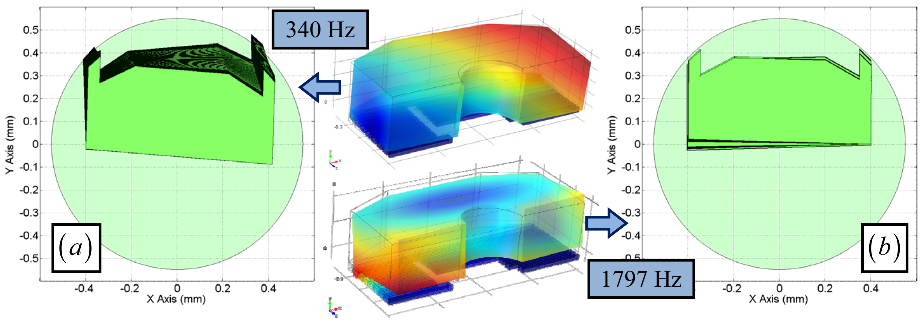

Fig. 8. Vibration patterns of the initial beta design: (a) 340 Hz and (b) 1797 Hz

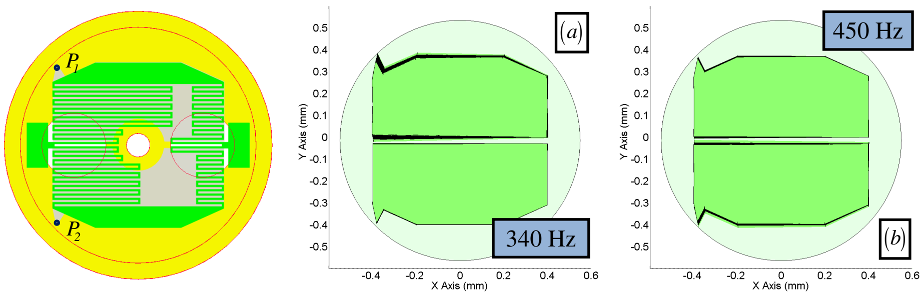

Fig. 9. The final beta design with its vibration patterns: (a) 340 Hz and (b) 450 Hz

5.3 Fabrication Attempts

The final beta design will be fabricated as three components as indicated in Fig. 7: i) the base, ii) the rotor, and iii) the layered spring-mass structure. Since no tiny components need to be placed and glued, this assembling task could be accomplishable.

The base and the rotor both have stepped structures and they would be fabricated by etching a silicon wafer through a series of masked lithography. The layered spring-mass structure would have the following fabrication steps, referring to Fig. 10:

a) A seed layer for nickel electroplating will firstly be sputtered on the backside of the wafer;
b) Lithography will be performed on the front side of the wafer to define the profile of the nickel blocks;
c) Silicon will then be removed by dry etching so that the nickel blocks could be electrically deposited;
d) The wafer will be polished and a layer of polycrystalline silicon will then be grown and etched to form the spacer layer to lift up the spring from the nickel blocks;

e) The Cu spring spacer was electroplated;
f) A Ti/Cu seed layer was applied and the spring defining photoresist will be formed;
g) The Cu spring will then be electroplated;
h) All silicon materials will be resolved to release the spring-mass structure.

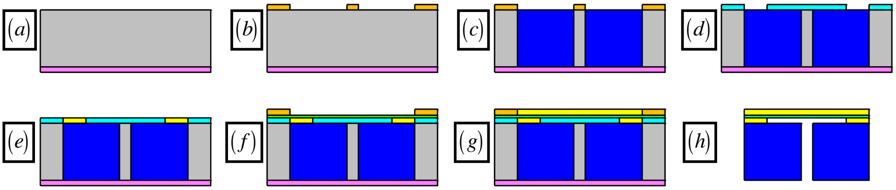

Fig. 10. Fabrication steps of the final beta design

6 Conclusions and Future Work

This paper presents two evolving designs, aiming at producing a micro actuator which can be selectively remotely actuated by weak resonant magnetic fields. If the proposed idea succeeds, these micro actuators can essentially directly harvest magnetic energy in space to perform mechanical work and they will find wide applications from MEMS manipulation to minimally invasive medicine.

The core design concept is to conceive various spring-mass structures where the mass blocks are made from soft magnetic materials and the springs are made from non-magnetic materials. A fast switching magnetic field will induce resonant vibrations of the mass blocks and the blocks would cause mechanical outputs via collisions or modulated friction when the vibrating amplitudes are big enough. Magnetic fields at different switching frequencies would then be capable of driving different rotary modes of different actuators.

Due to the fabrication and assembling challenges, the alpha design was evolved into the beta design. Design simulations and fabrication attempts for both designs were presented in detail.

The immediate future work is to finish fabricating the beta design. Then a series of experimental verifications and design characterizations could be carried out, investigating the i) feasibility, ii) speed of the rotation output versus strength of the magnetic field, iii) payload capability, iv) dynamic responses, v) further miniaturization possibility, etc.

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