Out-of-plane magnetic actuators with electroplated permalloy for fluid dynamics control

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Abstract

We have developed millimeter-scaled magnetic actuators capable of achieving large out-of-plane displacement and large forces using surface micromachining techniques in conjunction with electroplating of Permalloy (NiFe). Each actuator consists of a Permalloy piece attached to flexural cantilever beams, which are 400 μm long and 100 μm wide. Experiments show that under a 6 × 10^4 A/m external magnetic field, an actuator with the volume of the magnetic piece being 1 mm × 1 mm × 5 μm can reach a 65° angular displacement and exert a 87-μN force in the direction perpendicular to the substrate. We also discuss one potential application of controlling macroscopic fluidic mechanical systems using micromachined actuators. Results on using developed actuators to achieve rolling motion in a macroscaled delta-wing airfoil are presented. © 1999 Elsevier Science S.A. All rights reserved.

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1. Introduction

Technologies for developing micromachined actuators have been advanced significantly in the past two decades. However, to achieve large output force (on the order of tens of micronewtons) and long actuation range (100 μm and above) in microelectromechanical systems (MEMS) still poses many challenges. The electrostatic actuation, which is widely used in MEMS actuators, cannot always satisfy the desired range of force and displacement simultaneously under the constraints of practical microsystems. Other actuation methods, such as the ones based on bimetallic thermal actuation or shape memory alloy materials, are capable of producing the required displacement and force; however, their actuation capabilities are limited by the required temperature.

Microfabricated actuators are being increasingly used for fluid-control purposes. For these applications, a large force is required in order to allow efficient interaction with the fluid and to generate desired control effects. Magnetic actuation is potentially capable of realizing both large force and large displacement in an energy-efficient manner [1–3]. Wagner et al. [4] manually attached miniature permanent-magnet pieces on microfabricated suspensions and utilized integrated in-plane coils on the same chip to generate an external magnetic field. Liu et al. [5] developed an integrated coil-type magnetic actuator capable of achieving out-of-plane rotational displacement on the order of several hundred micrometers and magnetic forces with magnitude in the tens of micronewtons range. However, coil-type actuators typically require large biasing current (typically 50 mA) which, when coupled with a large number of turns in the coil, can translate into rather significant ohmic heating. Judy et al. demonstrated in-plane motion of a suspended polycrystalline silicon structure with an electroplated magnetic piece [6]. The actuator was driven by an external magnetic field and large deflection
angle (over 180°) has been demonstrated. In addition, Miller et al. [7] and Judy and Muller [8] have both developed individually addressable magnetic actuators. Moreover, complex electromagnetic subsystems, including a planar electromagnet [2] and magnetic micromotors [3], have also been realized in the past.

2. Fluid dynamical applications

Micromachined actuators have traditionally been used to control objects with similar or smaller dimensions or mass. Examples of these applications include microfluidic devices, microassembly [9] and mirrors for optical beam steering. As a novel objective of our current project, we plan to demonstrate that a collection of micromachined actuators can control macroscale objects, provided that a proper controlling mechanism exists [10]. The macroobject is a delta-wing airfoil, which is one of the fundamental configurations for generating lift forces [11,12]. Though the sizes of microactuators are much smaller compared with that of the delta wing, there exists a known fluid mechanism that allows microscale actuation to have an amplified, macroscopic effects (Fig. 1).

When laminar air flow impinges on the two leading edges of the wing at a certain angle-of-attack (Fig. 1a and b), two counter-rotating leading-edge vortices separate from the laminar flow and propagate over the wing’s top (Fig. 1c). These high-momentum, low-pressure vortices contribute two vortex lifting forces on the two sides of the wing; the sum of these two forces constitute approximately 40% of the total lifting forces at high angles of attack [13]. The strength and position of these two vortices are determined by the condition of the boundary layer, which is roughly 1–2 mm thick at a wind-tunnel flow speed of less than 20 m/s for a wing model with a chord of 30 cm.

The position and strength of the vortex is controlled by the location of the vortex separation, which can be influenced by airfoil geometry within the boundary layer itself. Small perturbation to the boundary layer can drastically change the characteristics of the separated vortices and the balance of lifting forces. We propose a new leading-edge control mechanism by employing arrays of millimeter-scaled, micromachined actuators. Specifically, two linear arrays of surface micromachined out-of-plane actuators (so called microflaps) can be placed along two leading edges of the delta wing (Fig. 1d). Flap arrays at rest remain at the bottom of the boundary layer, having no effect on the flow and vortices; when one array is deflected out of plane, however, it interacts with the boundary layer and artificially modify the separation point of the corresponding leading-edge vortex. The two vortex structures become unbalanced, and a macroscale rolling moment can be created. This unique mechanism can provide a new mode of maneuvering by eliminating the use of tail stabilizers, to increase energy efficiency and to achieve fast maneuvering of aircrafts.

In this study, micromachined actuators are required to deflect 1 to 2 mm out-of-plane (comparable with the thickness of boundary layers), and withstand large aerodynamic loading on the order of several hundreds of micronewtons. Microactuators can potentially sustain high fluid loading because they reside in boundary layers, in which the flow velocity and momentum is lowered compared with the free stream. These offer much higher mechanical response speed compared with macroscopic mechanical elements.

3. Actuator design

Fig. 2 illustrates the schematic diagram of a micromachined magnetic actuator, which consists of a suspended
magnetic piece. Its length, width, and thickness are designated as $L$, $W$, and $T$, respectively. The magnetic piece is supported by two cantilever beams, with their length, width, and thickness being $l$, $w$, and $t$, respectively. The bending displacement of the actuator due to its own gravitational weight is negligibly small.

The analysis of displacement as a function of the applied magnetic field is presented in the following. Since the regime of large angular displacement is the focus of our design, the Permalloy is modeled as a permanent magnet with the magnitude of its magnetization vector being equal to the saturation magnetization $M_s$. It should be noted, however, that under low magnetic field and angular displacement, the magnetization is not a constant but changes according to the applied magnetic field strength. Discussion of this topic can be found in Ref. [8].

Under the current assumption, we assume that two concentrated magnetic forces act at the upper and lower edges of the Permalloy piece (Fig. 3b). The magnitude of these two forces are:

$$ F_1 = M_s W T H_1 $$

$$ F_2 = M_s W T H_2, $$

with $H_1$ and $H_2$ being the magnetic field strengths at the top and bottom edges of the plate ($H_2 > H_1$ in the current configuration). The magnitudes of $H_1$ and $H_2$ are experimentally found and are linearly dependent on the distance to the substrate (Section 5.1).

The structure plate, along with the Permalloy piece, has a thickness of $t + T$. Nominal values for $t$ and $T$ are 1 and 5 $\mu$m, respectively. Its moment of inertia, $I$, is proportional to $(t + T)^3$ and is much greater compared with that of the cantilever beam, which has a thickness of $t$. The combined structure plate and the Permalloy piece can thus be considered as a rigid body. Based on this assumption, an equivalent force system is created by translating $F_1$ to coincide with $F_2$; this results in a torque termed $M_{mag}$ and a point force $F$ (Fig. 3c), both acting on the bottom edge of the structural plate. The magnitude of $M_{mag}$ and $F$ can be expressed as:

$$ M_{mag} = F_1 L \cos \theta, $$

$$ F = F_2 - F_1 = M_s W T (H_2 - H_1). $$

Because the displacement of the actuator is relatively large, conventional linear treatment is not valid in this case. A closed-form analytical solution cannot be easily found [14,15]. A finite element simulation software (ANSYS) is therefore used. However, the displacement must be calculated recursively and manually as the magnitude of the forces are related to the vertical displacement, which in turn depends on the magnitude of forces. The calculation process is inefficient. We are therefore motivated to find a simplified analytical solution.

Using the ANSYS finite element simulation, we have found that it is a good approximation to treat the displacements due to the moment and the force independently and add these results to calculate the actuator bending under the combined force and momentum. This assumption is valid when the force is relatively small. It significantly simplifies the analysis.

Beam displacement under $M_{mag}$ is solved first. The cantilever beam assumes the shape of an arc, with the radius of curvature being $r = EI/M_{mag}$. The angular displacement at the free-end of the cantilever beam is:

$$ \theta_{torque} = \frac{l}{r}. $$

The $y$ coordinate at the corresponding location is therefore:

$$ y_{torque} = r \left[ 1 - \cos \left( \frac{l}{r} \right) \right]. $$

The maximum angular displacement ($\theta_{force}$) and vertical displacement ($y_{force}$) due to force $F$ can be simply found using established linear models [15]. The maximum vertical deflection ($y_{max}$) and angular displacement ($\theta$) at the end of the rigid structural plate are:

$$ y_{max} = y_{torque} - y_{force} + L \sin (\theta_{torque} - \theta_{force}), $$

$$ \theta = \theta_{torque} - \theta_{force}. $$

We have designed the area of the Permalloy piece to be $1 \times 1$ mm$^2$. The supporting cantilever beams are 400 $\mu$m long and 100 $\mu$m wide, with the nominal thickness being 1 $\mu$m.

4. Fabrication process

The fabrication process for the magnetic actuator is summarized in Fig. 4 and described in detail below. In the
first step (Fig. 4a), a 3-μm-thick phosphosilicate glass (PSG) sacrificial thin film is first deposited on top of the silicon substrate at 450°C as a sacrificial material. It is patterned to form individual mesas on top of which actuators will be located. These mesas isolate individual actuators and limit the total amount of lateral undercut during the sacrificial-layer etching processing. This important feature provides robust process control and results in high structural yield and high area device of devices even when over-etching is encountered.

After removal of the photoresist layer, the wafer is annealed in nitrogen at 1000°C for 1 h. It is then covered by a layer of LPCVD polycrystalline silicon, which is subsequently coated with a 0.5-μm-thick PSG layer that serves as a complimentary doping source. During a 1-h, 950°C stress-relief anneal in nitrogen ambient, the polysilicon is doped symmetrically from both sides. This measure reduces the intrinsic-stress gradient across the thickness of the polysilicon and minimizes residue beam bending.

A conductive seedlayer (200-Å-thick Cr and 1800-Å-thick Cu) is thermally evaporated (Fig. 4b). During the electroplating process (Fig. 4c), the wafer is affixed to the cathode with a pure Ni piece as the anode. An external magnet (450 Oe) is applied with the field lines being parallel to the wafer substrate. This bias establishes directions of the easy axis within the Permalloy piece [16,17]. The easy axis is parallel to the length of the cantilever support beams. Electroplating takes place at a rate of 5 μm/h under a bias-current density of 8 to 12 mA/cm². Experimental B–H hysteresis curves of the Permalloy material (80% Nickel and 20% Iron [18]) along both the easy axis and the hard axis are shown in Fig. 5. The Permalloy material used in the current study show only a minor difference in magnetic properties, e.g., saturation magnetization, between the easy and hard axes. The relative permeability (μr) is 4500. Following the electroplating process the photoresist is removed and the exposed seedlayer material is then etched away by using Cu etchant (100:5:5 wt. water:acetic acid:hydrogen peroxide) followed by a Cr-mask etchant (either a commercial etchant [19] or diluted HCl (10 water:1 HCL).

Actuators are subsequently released by 49% HF within 20 min. The Permalloy material sustains HF etching without any structural or chemical damage. The polysilicon material is etched slightly, reducing the thickness of the cantilever beams. Since the structure plates have large surface areas and the supporting beams are soft (spring constant ~ 100 μN/1 mm = 0.1 N/m for cantilever beams), they can be easily pulled down by surface tension to the substrate and form permanent bonds if conventional drying techniques (e.g., spin drying) are used. To ensure high yield, the structural plate is levitated away from the substrate surface via magnetic interactions. This method effectively prevents the actuators from coming into contact with the substrate, therefore guaranteeing that 100% yield.

1 Cr mask etchant, Transene, USA.
is routinely achieved. Shown in Fig. 6 are top and perspective views of fabricated actuators.

5. Results and discussions

5.1. Actuator calibration in still air

We used an electromagnet to provide an uniform external magnetic field. The variation of $H$ with respect to the distance, $d$, to the substrate plane, is calibrated experimentally using a Gauss meter (Edmund Scientific). In a region near the surface of the core, $H$ decreases linearly with increasing spacing $d$, according to the following expression:

$$H = H_0(1 - \alpha d),$$

where $H_0$ is the strength of the magnetic field at the surface of the substrate, $\alpha$ is a scaling constant ($\alpha = 0.0267$ as determined by calibration).

5.2. Fluid dynamic control

A scaled aluminum delta-wing airfoil (Fig. 9) has a span of 40.35 cm and a sweep angle of 56.5°. It is mounted on a six-component transducer that records moments and forces in three axes. The magnetic biasing is provided by a rotational magnetic bar embedded within the leading edges of the delta wing and powered by a miniature stepping motor. The location of the actuators is indicated by the angle $\beta$ which is zero at the lower surface and 180° at the upper surface of the wing.

It was found that the region close to flow separation is very sensitive to small perturbation [21]. The innovation of this study is applying microactuators to manipulate the thin boundary layer near the leading edges of a delta wing, and consequently, alter the flow separation location. We used a micromachined shear-stress sensor [22] to measure the separation point along the leading edges of the delta wing.

Initially, time-averaged measurement of the rolling moment $M_{roll}$ was taken with the flaps kept on for at least 4 min. The resulting $M_{roll}$ at different wind-tunnel flow speed is normalized with respect to the vortex lift moment $M_{vl}$. Since only a single vortex is controlled, the resulting $M_{roll}$ at different wind-tunnel flow speed is normalized with respect to the moment produced by a single vortex.
Fig. 9. Photograph of a delta-wing model mounted in a wind tunnel, together with a close-up view of a leading edge of the wing, where actuator arrays are installed.

$M_{vl}$. Here, $M_{vl}$ is the product of the vortex-lift force on one of the leading edges multiplied by the distance from the centerline to the centroid of the half wing. The rolling moment is measured as a function of $\beta$ for various angles of attack $\alpha$ ($\alpha = 20, 25, 30,$ and $35^\circ$). The free-stream velocity is also varied from 10 to 35 m/s. Approximately 15% torque was achieved at an angle of attack of $25^\circ$ (Fig. 10). At $\alpha = 25^\circ$, a negative torque can be as large as $-12\%$ at $\beta = 80^\circ$.

The interaction between microactuators and vortices can be seen from flow visualization experiments [23]. Fig. 11a shows the vortex structure with an array of actuators located at $\beta = 50^\circ$ on the right-hand side of the wing. Also shown on the left-hand side in Fig. 11a is a picture of a single vortex without any actuator for comparison. It is clearly noticeable that vortex structure has been distorted by the presence of the microactuators. Since the location of the microactuators is ahead of the separation point, the

Fig. 10. Normalized rolling moment vs. locations of actuators at AOA $= 25^\circ$, with 1 mm-sized actuators.
flow could separate earlier due to the higher pressure gradient caused by the presence of the microactuator. It was observed that the core of the vortex has been moved outboard. A positive rolling moment could be generated by these unbalanced vortices.

At $\beta > 60^\circ$, the rolling moment becomes negative in all cases. Fig. 11b is the flow visualization picture of the vortex with a linear array of actuators located at $\beta = 80^\circ$. It was found that the core of the vortex had shifted inboard and the direction of the shear layer shedding from the leading edge had been suppressed. The possible mechanism for the phenomena is as follows: the flap actuator moves away from the surface and reduces the local curvature locally such that the adverse pressure gradient is reduced. As a result, the separation is delayed and the vortex moves inboard. A negative rolling moment could be generated by these unbalanced vortices accordingly. The negative rolling moment can be employed in conjunction with the positive-working rolling moment generated on an opposite leading edge. We have observed the sum of individual incremental torque equals the value obtained by the simultaneous actuation along both leading edges; it indicates that modifications of the vortices on both sides of a wing by the actuators seem to be independent.

6. Conclusions

Surface micromachined out-of-plane Permalloy actuator arrays have been developed for controlling the rolling moment of a tailless delta wing. The actuator consists of a millimeter sized electroplated Permalloy plate with supporting polysilicon beams and is driven by an external magnetic field. Large angular deflections (over $60^\circ$) and vertical deflections (on the order of 1–2 mm) have been demonstrated. The magnetic forces and flow loading involved in the flap operation is on the order of hundreds of micronewtons. Linear arrays of such flaps are positioned near the leading edges of a delta wing; wind-tunnel tests confirm that a rolling moment on the wing can be generated by the flap actuation. These magnetic actuators can have a number of applications, including fluid mechanics applications that are illustrated in this paper. Others include optical light modulators and microrobotics assembly systems.

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