DESIGN, FABRICATION, AND TESTING OF A MILLIMETER-LEVEL MAGNETICALLY SUSPENDED MICROMOTOR

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ABSTRACT

A magnetically suspended micromotor with 5 mm stator diameter and 1.5 mm rotor diameter, 0.1 mm air gap and 0.5 mm thickness has been built and tested. The stator and rotor are made by the UD LIGA process to achieve high dimensional accuracy. The micromotor is actively controlled using a four-quadrant photodiode to measure radial displacement. The system with UD LIGA rotor is successfully spun up to 600 rpm. A micro inductive sensor is proposed to integrate into the micromotor in the future. The micro inductive sensor designed for the first micromotor prototype has eight 15-turn single-layer coils with 10 µm line width, 10 µm line space and 6 µm thickness. The coils are fabricated using thick photoresist lithography and electroplating process. The sensor has a sensitivity of 44 mV/µm and error of 1.2 µm within 400 µm range.

INTRODUCTION

The study of magnetically suspended micromotors is to reduce the surface friction and wear in micromachine applications. Beams [1, 2] developed the first practical magnetic suspension for high speed rotating devices. In 1959, he successfully suspended and spun an 8 mm (1/32 in) steel ball over 10^7 rpm.

In 1993, Guckle et al. [3, 4] built a three-phase reluctance motor with a 6-pole stator and 4-pole rotor. The motor is made using the X-ray lithography and electroplating processes. The rotor has a diameter of 285 µm, thickness of 80 µm, and air gap of 3 µm. The stator has a much larger size with a thickness of 160 µm. Each pole has 6 turns of coils wire-bonded with 30 µm diameter wire. The rotor is passively levitated in the magnetic field to achieve a maximum speed of 34,000 rpm and output torque above 10^{-8} N-m.

Bleuler [5] in 1992 studied various types of micro active levitation and reported the advantages for the electrostatic and electromagnetic types. In 1993-4, Bleuler et al. [6] constructed a magnetically suspended micromotor with a 12-pole stator and 8-pole rotor. The micromotor is made by electro discharging machining (EDM) process. The rotor has an outside diameter of 7.9 mm, thickness between 0.5 and 1mm, and air gap of 0.1mm. The stator has an outside diameter of 80 mm and two windings at each pole, 100-turn winding for bearing and 20-turn for motor. The micromotor is actively controlled in the radial direction using a laser and four-quadrant photodiode. The micromotor was operated up to 3,000 rpm. Bleuler et al. also designed and built a second micromotor with a rotor diameter of 3 mm and thickness of less than 15 µm. The stator has 4 horseshoe type electromagnets fitting into an area of 6×6 mm^2. The second micromotor is fabricated using lithography and electroplating process on a silicon wafer. However, the second prototype is not yet tested for magnetic suspension.

Zmood et al. [7, 8] have developed micro inductive sensors and micro electromagnetic actuators since 1991. In 1999, Zmood et al. have successfully suspended a pancake type micro magnetic bearing. The stator has an outside diameter of 2 mm and thickness of 250 µm. There are 4 electromagnets inside the stator and each has 80-turn hand-wound coils. The rotor has an inside diameter of 2.02 mm, outside diameter of 2.6 mm and pole face thickness of 50 µm. The components of the micro bearing are made by thick photoresist lithography and electroplating before assembled together. The micro bearing is actively controlled in two radial axes using four micro inductive sensors. The hand-wound sensor coils are located at the rotor plane and two sensors measure each direction.

FIRST PROTOTYPE

The research of magnetically suspended micromotors [9, 10, 11] at the Huafan University first started in 1996. Two prototypes have been built based on reluctance force magnetic levitation principle. The first prototype made by EDM process has an 8-pole stator and 6-pole rotor. The micromotor has a rotor outside diameter of 8 mm, rotor inside diameter of 1 mm, stator outside diameter of 25 mm, stator inside diameter of 8.6 mm, air gap of 0.3 mm and thickness of 0.5 mm. A semiconductor laser and four-segment photodiode are used to measure the radial displacement of the rotor. A proportional and derivative (PD) controller is designed and built to achieve system stability. The prototype was spun up to 210 rpm to prove the design feasibility.

We have identified two major issues that must be solved before the cost of micromotors can reach economic scale for any serious application:

1. Microfabrication for mass production,
2. Part elimination for ease of assembly.

There is no instant solution for both problems but few intermediate steps can be addressed:

1. The LIGA-like process, which can achieve high aspect ratio, millimeter-level thickness, dimensional accuracy and low cost, is chosen for micromotor fabrication. The Ultra-deep (UD) LIGA process was selected for the project because the Synchrotron Radiation Research Center (SRRC) in Taiwan has accumulated many years of experience and offered a free academic service sponsored by the National Science Council. The thick photoresist, such as SU-8, integrated well with semiconductor process is considered as another good choice.
2. The positioning sensors for magnetic levitation are very expansive and difficult to assembly/adjustment so they must be either eliminated or integrated within the micromotor. The inductive sensor is a better candidate for integration since the coil-making step must be a part of the fabrication processes of the micromotor.

MILLIMETER-LEVEL MICROMOTOR DESIGN

The second micromotor prototype developed at the Huafan University is a millimeter-level magnetically suspended micromotor. This micromotor has been improved from the previous one at the following aspects:

1. System integration design of the micromotor is enhanced to meet the challenges of assembly, manufacturability, and testing.
2. New microfabrication technology UD LIGA is used to achieve better dimensional accuracy.
3. An observation system combining a CCD camera, semiconductor laser, new photodiode, and optical lenses is set up for assembly, testing, and control of the micromotor.

The millimeter-level micromotor has a stator outside diameter of 5 mm, rotor outside diameter of 1.5 mm, air gap of 0.1 mm, and thickness of 0.5 mm. The micromotor still use the design of 8-pole stator and 6-pole rotor. The design drawing of the micromotor is shown in Figure 1. The dimensions and characteristics of the micromotor are summarized in Table 1. The finite analysis computer software ANSYS is used to conduct the electromagnetic analysis and the simulation results are verified using a simplified reluctance model. Because of small dimension and high accuracy the stator and rotor are made using both EDM and UD LIGA fabrication methods.

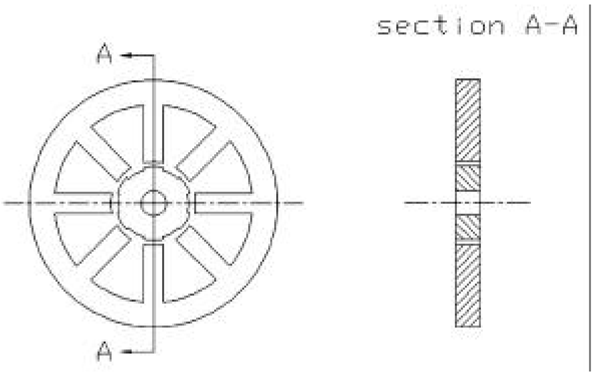

FIGURE 1: Millimeter-level Micromotor Design

TABLE 1: Millimeter-Level Micromotor Design

Description	Value
Stator Outside Diameter	5 mm
Stator Inside Diameter	1.7 mm
Rotor Outside Diameter.	1.5 mm
Rotor Inside Diameter	0.5 mm
Stator/Rotor Thickness	0.5 mm
Nominal Air Gap	0.1 mm
Stator Pole Number	8 poles
Rotor Pole Number	6 poles
Stator Mass	2.9 mg
Rotor Mass	0.6 mg
Turns of Each Coil	15 turns
Coil Diameter	50 μm
Coil Resistance	1.1 Ω
Bearing Bias Current	0.33 A
Kx (calculated)	19.75 N/m
Ki (calculated)	6.6×10^{-3} N/A
Motor Step Angle	15^{o}
Motor Excitation	1 or 2 Phase
Motor Excitation Current	0.2 A
Torque (calculated)	1.44×10^{-8} N-m

UD LIGA PROCESS

The ultra-deep (UD) LIGA process [12, 13] developed at the SRRC is originally used for die fabrication and can achieve a microstructure thickness of 2 mm and line width of 100 µm. The UD LIGA using successive exposure and conformal mask is different from conventional LIGA. The UD LIGA do not need a light source of high energy or X-ray membrane mask so the fabrication cost is cheaper. The successive exposure will reduce the developing time and achieve a high aspect ratio microstructure. The conformal mask will maintain a perfect alignment even after multiple exposures and development. If the conformal mask is made from a contact print as described below, the precision is up to 2 µm depending on the design of microstructure. The precision can be further improved within 1 µm if the laser write is applied.

The advantages of the UD LIGA are summarized as followings:

1. No alignment required,
2. Less exposure time and thinner absorber,
3. High fidelity pattern transfer,
4. Less thermal deformation,
5. High photoresist developing rate.

The UD LIGA process is illustrated in Figure 2 and 3. The key steps in the micromotor fabrication are:

1. Sandwich structure preparation,
2. X-ray conformal mask,
3. Successive exposure & development,
4. Electroforming.

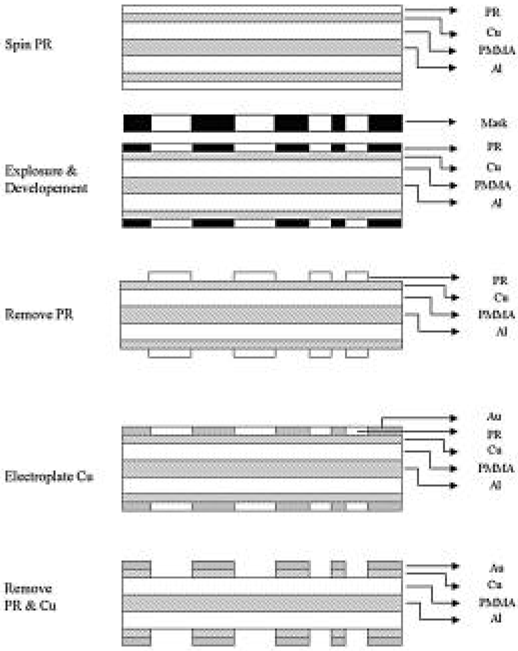

FIGURE 2: Conformal Mask

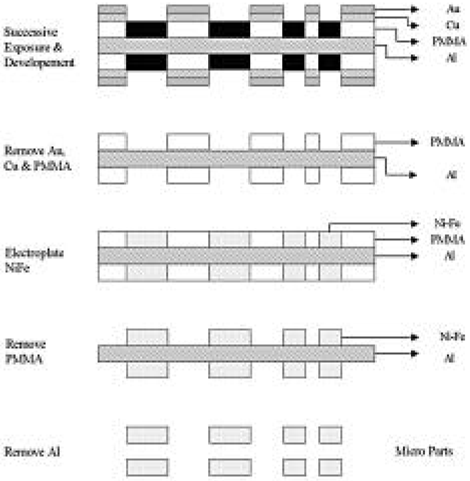

FIGURE 3: Exposure, Development & Electroforming

The first step is to prepare a sandwich structure of copper foils, PMMA sheets, and aluminum substrate. To improve the adhesion between Al and PMMA, the Al substrate is treated with surface roughening. The sandwich structure (Cu-PMMA-Al-PMMA-Cu) is glued, cold-pressed, and annealed to reduce any stress. The symmetric structure is designed to balance residual stress induced from electroforming process. The X-ray absorber is patterned using thick photoresist lithograph on the top of the Cu foil and then plated with 20 µm gold. The exposure parameters of the deep X-ray lithography is calculated based on exposure dosage, mask thickness, developing time, and depth (thickness of PMMA). The UD LIGA process can achieve a structure depth of 430 µm for a single exposure of 2100 mA-min/cm and 1000 µm for double exposure. Because there is no need of mass production the rotor and stator is directly electroformed using Ni-Fe alloy without making a mold. The micromotor components will be released after etching the Al substrate with 1 M HCl solution.

Figure 4 shows a SEM photo of the rotor made by the UD LIGA after surface polish. Figure 5 shows the EDM-made rotor. The precision for the UD LIGA is 4 µm and 20 µm for the EDM.

FIGURE 4: UD LIGA Rotor After Surface Polish

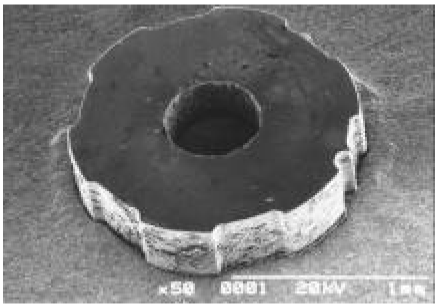

FIGURE 5: EDM Rotor

SYSTEM INTEGRATION AND TESTING

Because of the size of the micromotor it is impossible to adjust and control with the naked eye. An observation system combining a CCD camera, semiconductor laser, four-quadrant photodiode, and optical lenses is set up for assembly, testing, and control of the micromotor. The laser and photodiode must be tested and calibrated in-situs. The sensitivities for two axes are 20.4 and 23.2 mV/μm and the linearity error is less than 1 μm within the range of 120 μm.

An EDM made stator is used at the current micromotor and there are a total of 15 turns of wires wounded at each pole. Two different rotors fabricated by the EDM and UD LIGA methods are successfully suspended and spun. The micromotor using the UD LIGA rotor has achieved a maximum speed of 600 rpm but it can only reach 460 rpm with the EDM rotor. Figure 6 shows the magnetic suspension of the micromotor with the UD LIGA rotor. Figure 7 and 8 are the rotor displacement and X-Y plot at 500 rpm. The runoff error is measured less than 3 μm.

The limitation of maximum speed is mainly due to a small magnetomotive force. One way is to increase the maximum current in the micromotor to the wire current capacity of 0.8 A. The other way is to increase the winding distribution factor. It has demonstrated that 20 turns per pole can be achieved without problem. It is possible that an optimal design of the micromotor with smaller air gap is needed for a higher speed.

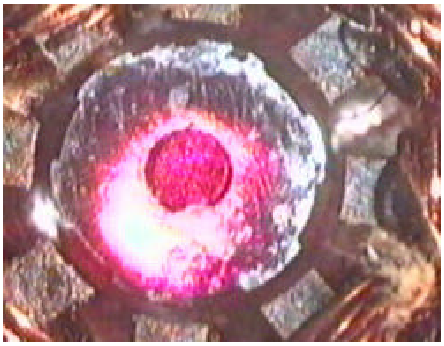

FIGURE 6: Magnetic Suspension of the Micromotor

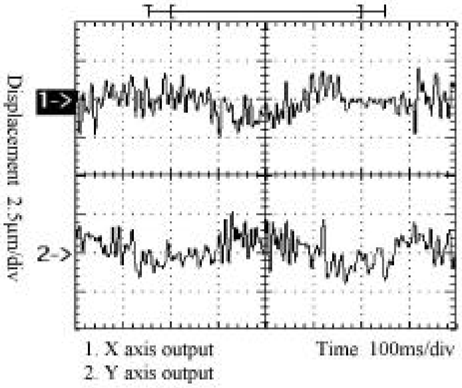

FIGURE 7: X &Y Displacement at 500 rpm

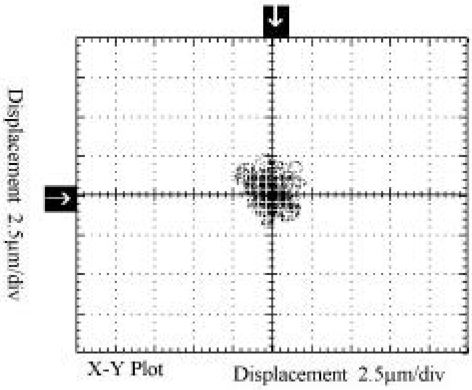

FIGURE 8: X-Y Displacement Plot at 500 rpm

MICRO INDUCTIVE POSITIONING SENSOR

Although a semiconductor laser and four-quadrant photodiode are used to measure radial displacement in the micromotors they are the first to be replaced from an integral design viewpoint. The laser and photodiode are required separate handling, securing, assembly, adjustment, and checking processes. It is even worst that both use different material and manufacturing process from the micromotor. An inductive sensor is a better choice based on fabrication, assembly and cost. However, the conventional multi-layer wire-winding process is difficult to duplicate using semiconductor technology. It is much easy to fabricate an inductive sensor using planetary coils with limited number of layers.

A innovate design of the micro inductive positioning sensor is proposed as shown in Figure 9. The micro sensor is fabricated using thick photoresist lithography and electroplating process on a silicon substrate. The silicon substrate is parallel to the micromotor with a minimum distance. The sensor coils are located just outside the air gap between the rotor and stator so the radial displacement of the rotor will change coil inductance. The inductive sensor is a differential type and has two coils at opposite air gaps for one radial axis.

There are a total of eight coils so four extra coils can be used as an encoder to detect the rotor position and direction of rotation. Since the sensor is made by the semiconductor technology the extra cost will be minimum.

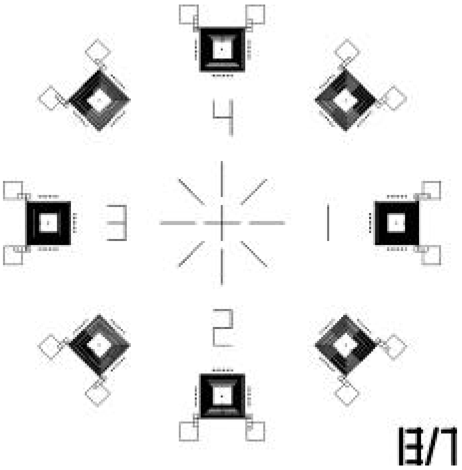

FIGURE 9: Micro Inductive Positioning Sensor

To prove its feasibility the micro inductive sensor is designed for the first micromotor prototype with a rotor outside diameter of 8 mm and air gap of 0.3 mm. There are eight coils uniformly located at the diameter of 8 mm circle. Each sensor coil has 15 turns of wire per layer in 1mm^2 footprint. Three photomasks are designed to make single or double layer coils with different patterns. The single layer coil tested for the design has a line width of 10 µm, line space of 10 µm, thickness of 6 µm, and inductance of 200 nH as shown in Figure 10.

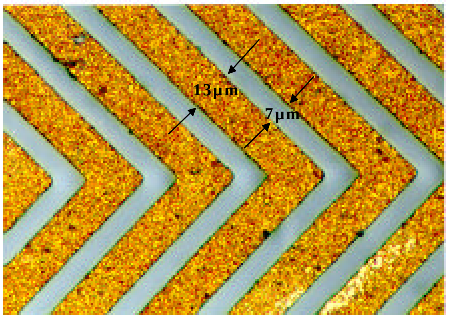

FIGURE 10: Single Layer Inductive Sensor Coil

The micro inductive positioning sensor with amplitude modulation circuit is tested using unpolar rotor (with no pole) as the target. Various experiments are conducted at oscillating frequencies of 8, 10, and 12 MHz with heights of 350, 400, 450, 500, and 550 µm above the sensor. Figure 10 shows the sensor output voltage versus radial displacement of the rotor at 12 MHz with different heights. Table 2 includes all the testing results of the inductive sensor.

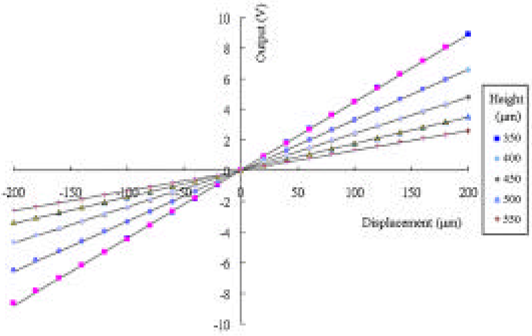

FIGURE 11: Inductive Sensor Output at 12MHz

TABLE 2: Inductive Sensor Testing Results

Frequency (MHz)	Height (µm)	Sensitivity (mV/µm)	Error (µm)
8MHz	350	29	1.07
	400	22	1.14
	450	16	1.71
	500	12	2.29
	550	9	2.68
10MHz	350	38	1.09
	400	28	1.16
	450	21	1.28
	500	16	1.33
	550	12	1.70
12MHz	350	44	1.16
	400	33	1.20
	450	24	1.31
	500	17	1.44
	550	13	1.54

The experiments show that the sensor output voltage is proportional to the radial displacement and oscillating frequency but inversely proportional to the height between the target and sensor. The sensor sensitivity can reach to 44 mV/µm at 12MHz within the range of 400 µm. The linearity error is 1.2 µm and drift is 15 mV. It is noted that the modulation/demodulation chip LM1496 contributes most of drift error.

CONCLUSION

This paper reports the design, fabrication, and testing of a millimeter-level magnetically suspended micromotor. The micromotor has a stator outside diameter of 5 mm, rotor outside diameter of 1.5 mm, air gap of 0.1mm, and thickness of 0.5 mm. The stator and rotor are manufactured by both the EDM and UD LIGA methods. The UD LIGA process using successive exposure and conformal mask can achieve high aspect ratio structure and good dimensional accuracy. A CCD camera system combining with a laser and four-quadrant photodiode is used to measure and monitor the radial displacement of the rotor. The micromotor with UD LIGA-made rotor is successfully suspended and spun up to 600 rpm.

An innovate micro inductive positioning sensor design is proposed to replace the laser and photodiode. The micro inductive sensor made from thick photoresist lithography and electroplating processes has advantages of low cost, manufacturability improvement, and ease of assembly. The inductive sensor is designed with eight single-layer coils uniformly located at the diameter of 8 mm circle. Each coil has 15 turns of wire with a line width of 10 µm, line space of 10 µm, and thickness of 6 µm. The sensor is tested with the 8-mm unpolar rotor and its sensitivity is 44 mV/µm at an oscillating frequency of 12MHz and height of 350 µm within a travel range of 400 µm. The linearity error is 1.2 µm and drift is 15 mV (0.3 µm). The micro inductive sensor will be integrated and tested using the first micromotor prototype in the future.

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