MICROMACHINED ACTIVE MAGNETIC BEARINGS

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ABSTRACT

A disc-shaped rotor of 8 mm diameter and 1mm thickness has been levitated and rotated up to 3000 rpm in a miniature magnetic-bearing-motor combination. The levitation type is actively controlled using an optical sensing system in two radial directions. A second rotor of 15 µm thickness and 3 mm diameter is now being built along with four miniature stator magnets using micromachining technology of read-write magnets of disc storage devices. The machining consists of lithographic and electroplating processes. The bearing will be combined with an induction motor. Possible applications could include rate gyros.

1. INTRODUCTION

Mechanical friction and wear are surface effects scaling down with the second power of length. Load forces such as weight and inertia on the other hand scale down with the third power of length. Therefore the dominant limits on performance of micromachines are tied to friction and wear. As an example, a micro-motor rotating at 10000 rpm is already quite an achievement /Fujita 1/. However the limit of rotational speed performance in traditional machines is given by the resistance to centrifugal force would be by orders of magnitude higher. As a consequence, contact-free levitation of parts is an essential step in increasing the performance of micro mechanical devices.

Among all possible levitation principles /7/, active electromagnetic levitation has dominated practical applications for various reasons. An important point speaking for an actively controlled system is the inherent possibility of high precision position control, a necessary feature for many applications.

Small spheres have been levitated and rotated electromagnetically already in 1950 by Jesse W. Beams /2/ with electronic tube controller-amplifiers. Spectacular rotational speeds have been reached up to the bursting under centrifugal force (10^7 rpm for rotors of the mm order of magnitude). This gives an idea of the potential of micro magnetic bearings.

2. ACTUATOR AND SENSOR SETUP

For this project it was decided to realize a disc-shaped rotor in place of the sphere-shaped rotor since fabrication processes for micro-machines favor two-dimensional structures. The true micro-motors realized up to now have disc-like rotors and not spherical or cylindrical rotors. It was decided to build a rotor with two active degrees of freedom, the radial directions x and y, (fig. 1). The vertical direction (z-coordinate) and the tilt around the x- and y-axis are only passively stabilized.

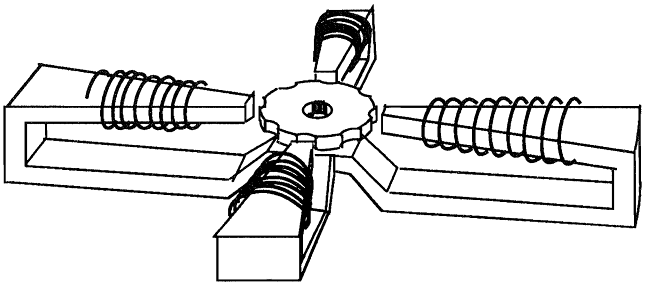


Fig.1 Stator for the two radial (horizontal) directions x and y.

Displacement in the horizontal x-and y-directions is done by a four-segment photodiode below the rotor and by directing light from the top through a hole in the center of the rotor. The basic arrangement of the sensor system is shown in Fig. 2 , along with the stator. A precision of the 0.1 µm order or better can be achieved with such sensors. A differential measurment principle is used making this sensing method relatively robust to variations in laser intensity.

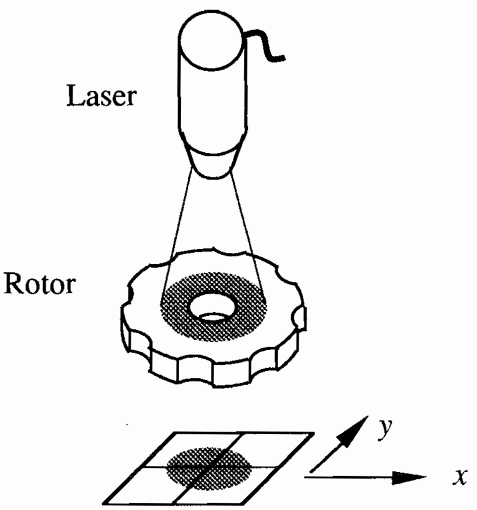


Fig. 2 Optical sensor system for measurement of the two translational movements in x– and y–direction. It is possible to use normal light, sensitivity to ambient light is reduced by using the laser.

3. FIRST PROTOTYPE

A first system with 7.9 mm disc-shaped rotors has been described earlier /3,4,5/. In this earlier version, the stator was not yet miniaturized.

The bearing has to be combined with a motor. For this first prototype, a stepping motor was chosen. With a 12-pole stator it is very easy to separate bearing and motor functions. The motor has three phases at each of the four bearing poles. The stator has two windings on each pole, made by hand. One winding (100 turns) is for the bearing and another one (20 turns) for the motor. Rotor thickness was between 1 mm and 0.5 mm, the system could be operated with several different rotors.

Rotors and stator were machined by electro discharge machining (EDM). The 7.9mm rotor has 8 poles for operation as a stepping motor. The stator has 8.1 mm inner and 80 mm outer diameter and is used as a bearing for two actively controlled radial degrees of freedom and a stepping motor at the same time. The other degrees of freedom, the two tilt angles and the axial (thrust) direction, are passive, i.e. the rotor is "pulled in" by the magnetic field without control.

This system was operated successfully up to 3000 rpm. Control of the contact-free levitation is with a digital signal processor at a control bandwidth of about 5 kHz. The levitation is robust, several different rotors could be inserted without problems.

4. SECOND PROTOTYPE: MICROMACHINED SYSTEM

The new system is a true micro-machine. For the second prototype, rotor *and* stator are miniaturized. Machining of rotor and stator is done by lithographic fabrication processes combined with electroplating.

The configuration of the first system has been successful, so it is retained for the new system. One important point has to be altered. In order to simplify the production process of the stator, the 12-pole configuration with 24 windings has been reduced to 8 poles with just four windings. The stator consists of four horse-shoe type magnets in a plane. The rotor has no poles. This means that reluctance-type motor such as the stepping motor operation is no longer possible. The new system will have to combine magnetic bearing and inductance motor /6/.

The rotor has a diameter of 3 mm and less than 15 μm thickness. The whole system including the four stator electromagnets, fits on a 6x6 mm square. Fig. 3 shows a photograph of the batch-fabricated stator. The magnets have a horse-shoe shaped core of permalloy and 36 turns of copper conductors grown by electroplating to about 2 μm thickness. The rotor and the magnet cores are of permalloy (Ni:Fe 80:20) also grown by electroplating. The thickness of the permalloy is about 10 μm. Initial calculations show that levitation should be achieved at about 30 mA current.

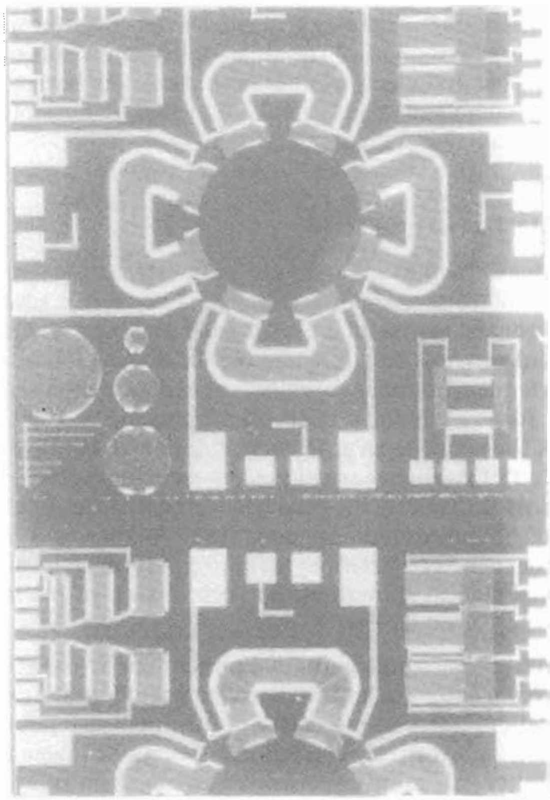


Fig. 3 Micromachined magnetic bearing stator. The four horse-shoe magnets with permalloy core and copper windings are clearly visible. The area shown is ca 1.5cm by 1cm (Tang, Hsieh, Miu, Tai, Caltech)

Figure 4 shows a cross section through the system including the photo sensor and the laser beam coming from the top.

In the next figure (5), some intermediate stages of the machining are shown. Ten masks are necessary. The stator process flow consists of 17 steps and the rotor process flow of 9.

The next photograph (Fig.6) shows a batch of stators. It is conceivable to produce magnetic bearings in batch thereby realizing great cost reductions. At the present time of course, electronics is still "conventional", that is not integrated on the chip. Present research concerns the control bandwidth necessary. For small systems analog control might be necessary due to the high bandwidth requirements.

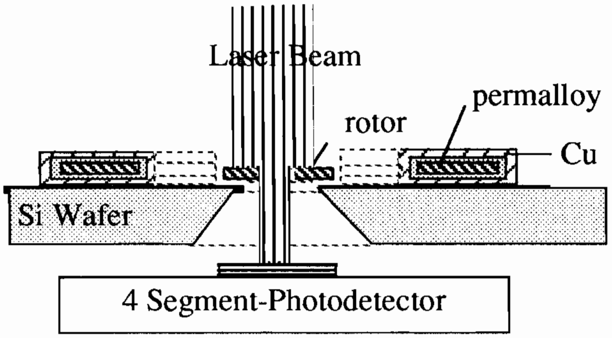
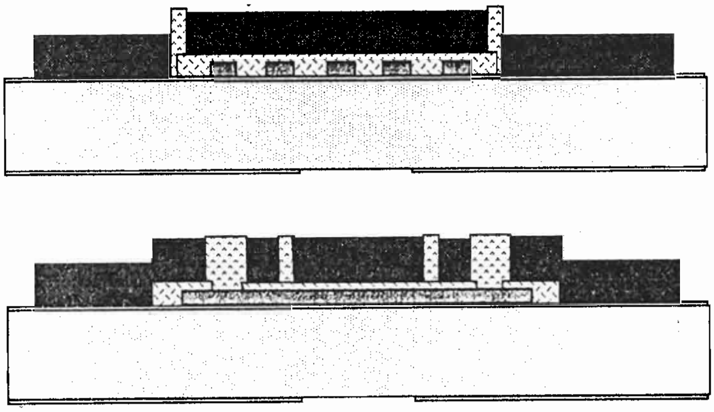
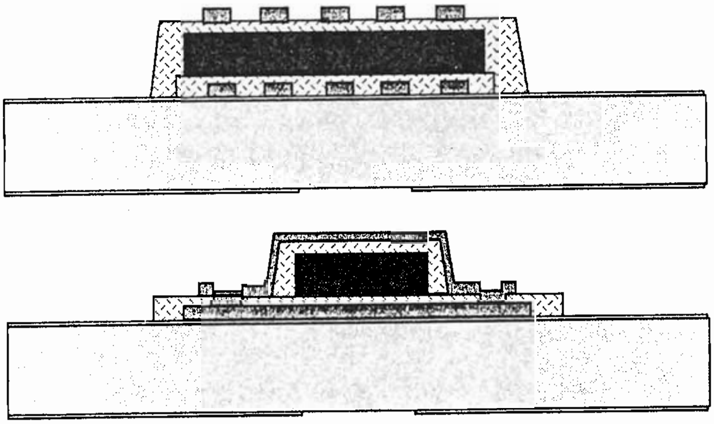


Fig. 4 Cross section of the micromachined electromagnetic bearing system. The rotor and the magnet core are of electroplated permalloy (Ni:Fe 80:20) of about 10 μm thickness. The winding is of electroplated copper (about 2 μm thick), core and winding are isolated by a 2 μm thick layer of resist. The surface of the silicon wafer has an oxide layer of 0.5μm thickness.



Step 11, longitudinal and transverse sections



Step 17, longitudinal and transverse sections

Fig. 5 Longitudinal and transverse cross sections of the coil for process step 11 (electroplating of 10μm of permalloy) and 17 (electroplating of the last layer of copper). Horizontal and vertical dimensions not to scale. (Tang, Hsieh, Miu, Tai, Caltech Micromachining Lab)

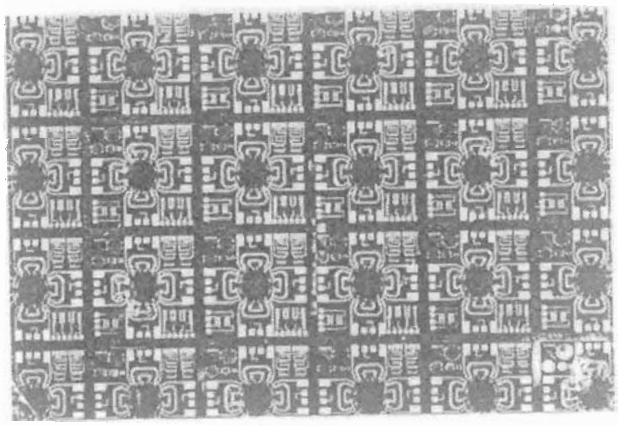


Fig. 6 Batch of magnetic bearing stators on a silicon wager along with test rotors and coils for process calibration. One unit square is 1cm by 1cm. (Tang, Hsieh, Miu, Tai, Caltech Micromachining Lab)

CONCLUSION

A magnetic bearing-motor system with a disc-type rotor of 8 mm diameter and 1 mm thickness has been realized and operated as a stepper motor. In this first experiment of micro active levitation, it is tested how optical sensing, digital control and electromagnetic actuators have to be designed and how they behave on such a scale. It has been demonstrated that the expected functions can be performed by all components and that further down/scaling seems quite possible. In a second prototype, now being manufactured, micromachining techniques are applied to obtain a very small stator and rotor.

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