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Towards Micro Magnetic Bearings
磁気軸受の小型化へ

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In order to avoid friction problems of micro devices, contact-free levitation methods are sought. With this project, a magnetic bearing for a disc-like rotor of 8mm diameter and 1mm thickness has been realized as a preliminary experiment to study scaling laws and possible approaches for very small magnetic bearings. The prototype has two actively controlled degrees of freedom for the suspension. The rotational angle of the rotor is also controllable, it has been designed as a simple stepper motor with an angular resolution of 1/48th of a full revolution. There seem to be no basic limitations to further down-scaling. The experiments described here were done at IIS as a masters thesis of F. Moesner and M Rohner.

1. INTRODUCTION

It is well known that mechanical friction and wear are among the major difficulties in micro mechanical devices. The reason is of course, that friction and wear are associated with surface area whereas the dominant forces in large machinery come from volume-related effects such as inertia and weight which decrease in relative importance with the down-scaling. Contact-free levitation of parts is therefore of special interest for micro machines.

The two basic possibilities for contact-free leviation are either passive (e.g. Meissner-Ochsenfeld) or active, i.e. with the help of a control loop. While some publications on micro levitation deal with passive levitation /1/, /2/, to our knowledge no actual experiments of active micro-levitation devices have yet been reported. Active devices, although more complex than passive ones, offer a significant advantage. In an active device, stiffness and damping of the support can be fine tuned in many degrees of freedom, according to the actual need, unlike passive support, where there is not much choice of the support characteristics once levitation has been achieved. Frequency dependent and adaptive behavior is possible, according to load and disturbance force. Forces and positions are sensed, and can be monitored, controlled and adjusted on line.

Apart from aerodynamic effects, there are three types of forces for possible active levitation: Electrostatic, electrodynamic (Lorentz force) and electromagnetic (reluctance force). The last one is used for large-scale magnetic bearings. Electrostatic devices require relatively high voltages, although sufficient down-scaling will produce interesting forces also at low voltages.

One of the drawbacks of electromagnetic bearings for micro levitation is the difficulty of miniaturizing the electromagnet with its coil. For the time being, this bearing type might therefore be interesting mainly for an intermediate range and not for the true micro scale range. As an example, motors in the millimetre order of magnitude have successfully been realized based on the electromagnetic principle /3/, /4/ and, in some cases, comparison with electrostatic devices has been made /5/. Active electromagnetic bearings are basically similar to electric motors (especially to reluctance motors as in /3/), therefore it may be expected that electromagnetic bearings can be realized in the same order of magnitude as the motors /3/, /4/ and /5/. The rotor of the motor in /3/ is a disc of 2.5 mm in diameter and 500 μm thickness, the electromagnetic motor described in /5/ fits into a space of

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10 mm^3 and the DC motor /4/ fits into a 5mm long casing with an outer diameter of 3mm.

In this preliminary experiment, the electromagnetic principle is favored over the electrodynamic principle. Thus a simple rotor of ferro-magnetic material can be used, no permanent magnetization of the rotor is necessary. One of the purposes of the experiment is to test the limits of applicability of the electromagnetic principle. It will have to be investigated in other projects how electrostatic and electrodynamic levitation devices can be miniaturized.

2. Basic Actuator Setup

The most simple AMB setup is the following: A ferromagnetic sphere is suspended below a single electromagnet. To stabilize the contact-free equilibrium position, only the vertical diaplacement has to be measured, e.g. with an optical sensor. The sensor signal is input to the controller of the power amplifier driving the electromagnet. This simple active magnetic bearing system controls one degree of freedom (the vertical, z-direction) actively, the x and y directions are said to be passively stabilized (the sphere is "pulled" under the magnet) while the three rotational degrees of freedom are not controlled, they are stabilized by eddy currents and air friction which stop any rotational movement after a short period of time. Such magnetic bearings have actually been built with great success already in 1946 by Jesse W. Beams (Univ. of Virginia) /6/ with electronic tube controller-amplifiers. The supported spheres were balls from ball bearings. Through induction, they could be made to rotate up to spectacular rotational speeds. The limit of the rotational speed is the centrifugal stress of the rotor. This in turn depends on the surface velocity, i.e. a smaller rotor will tolerate a higher rotational speed before bursting. Small spheres of the mm order of magnitude have thus reached rotational velocities of up to 10^7 rpm. This shows that micro magnetic bearings have the potential of alloing record-braking rotational velocities.

In this experiment, 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 micromotors realized up to now have disc-like rotors and not apherical or cylindrical rotors. Although it is possible to support a disc-like rotor with just one active degree of freedom (fig. 1), it was decided to build a rotor with two active degrees of freedom, the radial directions x and y, as shown in fig. 2.

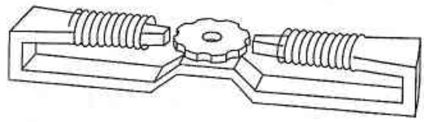

Fig. 1 Basic setup for support of a with one actively controlled degree of freedom. The sensor is not shown. The disc is dented in order to allow reluctance motor operation.

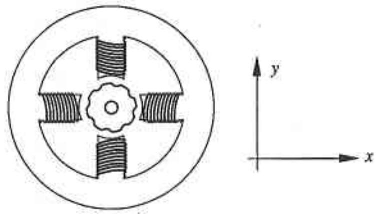

Fig. 2 Setup for support of a disc in two active degrees of freedom. The flux path of each pole is closed over the other three poles, in this way it is possible to move the disc in the plane of the drawing. Only three magnetic poles would also suffice. For the present experiments, the four pole basic arrangement was chosen in order to decouple the actuators in x- and y-direction

In these basic actuator configurations, the vertical direction (z-coordinate) and the tilt around the x-and y-axis are only passively stabilized.

3. Sensor System

The only sensing is displacement in the horizontal x-and y-directions. This can effectively be done by placing a four-segment photodiode below the rotor and by directing light from the top through a hole in the center of the rotor. Such multi-segment photodiodes are readily available in various sizes since they are stadard components of the tracking-focussing control of CD players. The basic arrangement of the sensor system is shown in Fig. 3, such a sensor system can be combined with the actuator of Fig. 2.

4. Motor

Before the complete bearing system is designed, the driving motor principle must be decided. There are the two basic possibilities of a reluctance motor or an induction motor. Since space is limited, the rotor of the bearing and the motor has to be combined, an assembly

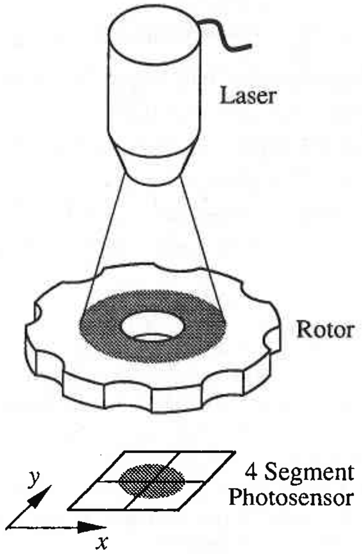

Fig. 3 Optical sensor system for x- and y-displacements. It is possible to use normal light, sensitivity to ambient light is reduced by using a laser.

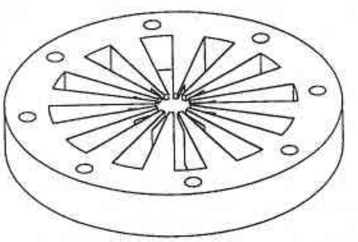

Fig. 4 Stator with 12 poles. The thickness of the poles is 1.5 mm at the center bore (diameter 8.1 mm) The rotor has a diameter of 7.9 mm, resulting in an airgap of 100 μm. Stator and rotor were machined by electric discharge (spark erosion) at the workshop of SEIKEN.

of different rotor parts, as it is usual for macroscopic bearings, has to be avoided.

A combination of an induction motor and a electro-magnetic bearing is possible and has been reported by Wehberg /7/ for a large scale AMB. Driving coils and bearing coils are wound on the same stator. This motor-bearing concept seems to allow a reduction to the millimetre order of magnitude. A further simplification might be achievable in combining drive and bearing coils and by eliminating either the active thrust bearing or by replacing one of the radial bearing-motor units with permanent magnets.

A combination of reluctance motor and magnetic

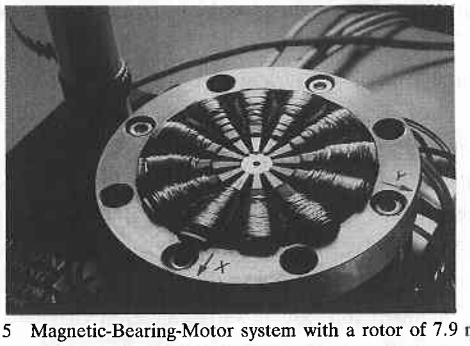

Fig. 5 Magnetic-Bearing-Motor system with a rotor of 7.9 mm diameter and 1 mm thickness.

bearing is reported in /8/. In our experiments, a reluctance motor was realized, the induction motor will be realized later on. An arrangement of 12 stator poles and 8 rotor poles was selected, smaller systems can be realized with less poles. Each pole carries 100 windings for the bearing and 20 windings for the motor. No attempt was made to reduce the stator size to the minimum. The behavior of small magnetic bearings depends mainly on the rotor mass, the stator size has not much influence. As this was a student project starting form zero and limited to a time of four months, work concentrated on a small rotor only. The stator with an outer diameter of 80 mm and an inner diameter of 8.1 mm is shown in Fig. 4:

5. Signal Conditionning, Control and Power Amp

The signal conditionning for the four-segment photodiodes and the power amplifiers could be taken with only slight modifications from the linear slide project of the Kawakatsu lab. The input to the controller are the signals of displacements in x-and y-direction as produced by the conditionning electronics. The controller itself is a new component . A floating point digital signal processor is used. The control algorithm for the two-channel control is programmed in C-language. A simple PID control is employed. Additional software is used for the difficult calibration task of the sensors, i.e. setting the correct offset values of the sensor signals, and for the reluctance motor. At the present stage, the software permits moving forward or backward in single-step mode, one step being 1/48th of a full revolution. In continuous rotation, 3000 rpm have been reached.

On of the main results is, that a sampling rate of 30kHz and a control bandwidth of about 7kHz are enough to obtain a robust stabilization of the magnetic bearing: The rotor can even be pulled out from a position underneath the stator at a lateral offset of one or two mm. The bearing control also is robust when the stepping motor is operating. This proves that the main obstacles have been mastered, what remains to be done is essentially fine tuning of the software in order to obtain higher rotational speed.

The actuators have four control channels (x-and y- in positive and negative direetion each), the bearing windings of three coils are in series for each channel. The motor windings are connected in three phases of four coils each, so that an additional three amplifiers are needed for the motor. This brings the total number of output channels handled by the DSP to seven.

More details are found in the diploma project /9/. The photograph (Fig. 5) shows the complete system.

6. 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 disigned 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. Future experiments will have to include higher rotational speeds, the induction motor principle and new fabrication processes for smaller rotors and stators. Optical sensing and electromanetic actuators seem possible for smaller systems, but digital control might soon reach a bandwidth limit.

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