Application of Magnetic Bearing for Contactless Ultra High Precision Positioning

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Abstract: Experimental results are presented of a big and small magnetically beared horizontal positioning table with absolutely no contact. Submicrometer positioning accuracy was achieved at long strokes.

The interaction between suspension and propulsion is treated and proves to be negligible during normal operation, which is verified by measurements. Several sensor types were applied resulting in different bearing performance characteristics.

Finally the current research program at the Laboratory for Micro Engineering is treated.

1 Introduction

One of the most challenging tasks in precision engineering is positioning with both high accuracy and long stroke. This has been researched quite extensively by Trumper, see [1, 2, 3]. A good example of a submicrometer accuracy positioning system can be found in an IC-lithography wafer stepper. In a wafer stepper two perpendicular motions must be achieved within a plane (called X-Y motion). The other degrees of freedom must be kept within very tight tolerance bands, typically in the order of tens of nanometers. The guidance of the wafer-stage must not show any wear for this would degrade the accuracy of the system and worn off particles will contaminate the wafer. Recent developments have shown that a good alternative for air-bearings is needed in modern wafer steppers. Magnetic bearings may just be that alternative.

The Laboratory for Micro Engineering has set itself a challenge in trying to build a magnetic suspension and propulsion system with long stroke (up to several tens of millimeters) and with submicrometer accuracy both in suspension and in propulsion direction.

In order to achieve this goal, Frank Auer has designed a Suspension and Propulsion Unit (short: SPU) that can perform these tasks. Previous publications about this SPU are [4, 5, 6]. The research was supported by both PHILIPS CFT, of the NEDERLANDSE PHILIPS BEDRIJVEN B.V. and the TECHNOLOGY FOUNDATION (STW).

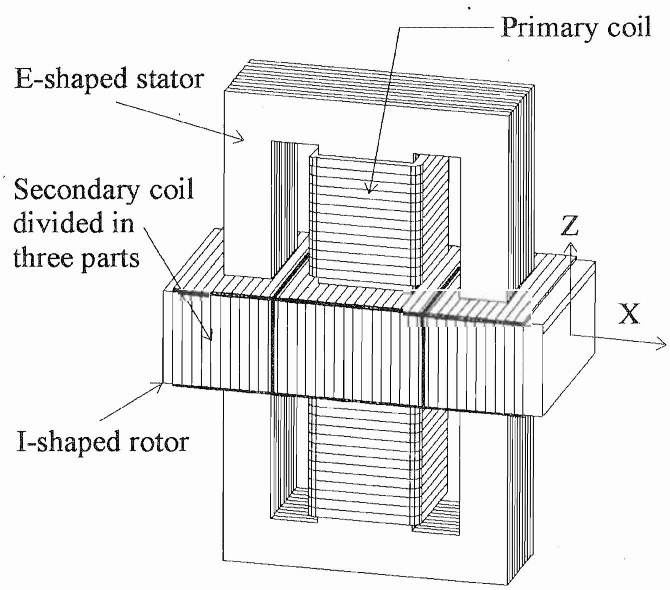

Fig.1: A schematic drawing of the SPU unit showing the primary reluctance coils and the secondary Lorentz coils around the rotor. The Z and X direction indicate the suspension and propulsion direction respectivily.

2 Principle of operation

The SPU is schematically drawn in figure 1. As can be seen in this figure, the magnetic suspension of the SPU is formed by a conventional type of magnetic bearing for linear motion. Two E-shaped electro-magnetic reluctance actuators provide a magnetic field for the bearing function, but this magnetic field can also be used for the propulsion function of the SPU.

In order to achieve a propulsion force that is perpendicular to the magnetic bearing direction, a secondary coil has been wound around the rotor of the SPU. Interaction of a current through the secondary coil with the magnetic field of the bearing, provides thrust to the rotor. This thrust is a Lorentz force. The Lorentz force F_L for the SPU is given by

$$F_L = 2 \cdot N_{sec} \cdot \mu_0 \cdot \mu_r \cdot I_{sec} \cdot b \cdot \left(\frac{I_0 - \delta I}{S_0 + \delta z} + \frac{I_0 + \delta I}{S_0 - \delta z} \right), \quad (1)$$

where

N_{sec}	=	the number of secondary coil turns	[-],
μ_0	=	the magnetic permeability of vacuum	[H/m],
μ_r	=	the relative magnetic permeability	[-],
I_{sec}	=	the current through the secondary coil	[A],
b	=	the width of secondary windings inside the magnetic field,	[m],
I_0	=	the primary coil stationary current	[A],
δI	=	the suspension control current	[A],
S_0	=	the nominal air-gap	[m], and
δz	=	the position deviation from equilibrium in suspension direction	[m].

In this way the magnetic field is used twice, a property that makes the SPU unique [7]. Thus, a very compact system can be built. The interaction between the propulsion force and the suspension force in the SPU is minimal, as will be treated in the next section. So, with this actuator, two perpendicular degrees of freedom can be controlled.

3 Interaction

An important issue is the mutual interaction between Suspension and Propulsion. It is important that a stable and stiff magnetic bearing keeps its functionality if secondary coils are placed inside the air-gap and fed with a current. It is inevitable that the design approach of the SPU leads to interaction between the suspension and propulsion forces. The interaction can be described from two points of view. Both points of view will be discussed below.

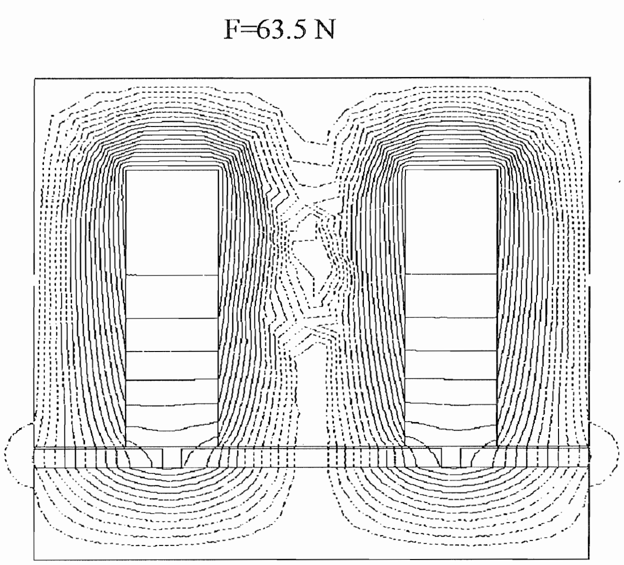

Fig.2: Finite Element Analys of the top half of an SPU. The graph shows the flux distribution when the secondary current equals zero. Note the symmetry of the distribution. The reluctance force (normal force) is indicated.

3.1 The influence of the propulsion on the suspension

Figure 2 and 3 show two finite element computations of the layout of the magnetic field. Figure 2 shows the magnetic field plus the magnetic forces when no current flows through the secondary coils. Note the symmetry of the magnetic field.

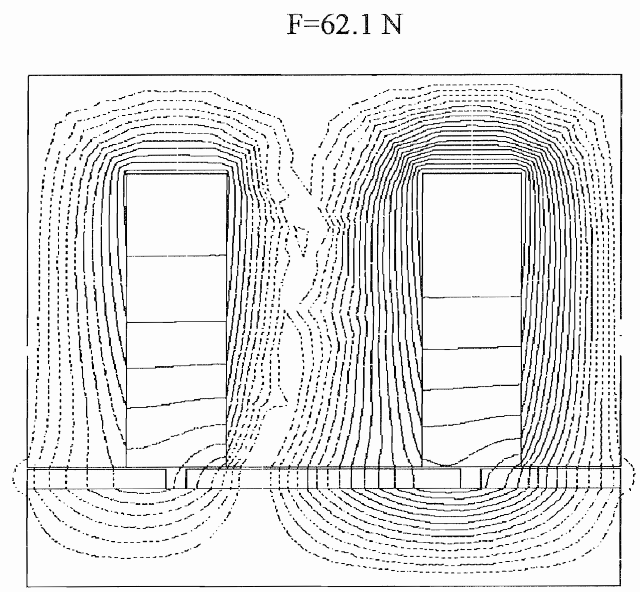

Fig.3: Finite Element Analysis of the top half of an SPU. The graph shows the flux distribution when the secondary coils carry a small current. The flux distribution is no longer symmetric, but the suspension force stays the same. The reluctance force (normal force) is indicated.

Figure 3 shows the magnetic field plus the magnetic forces when a relatively small current is sent through the secondary coils. Now the force changes a little bit. Note that the suspension force stays the same, while the propulsion force is generated. This indicates that the propulsion will not influence the suspension.

Things will change when too much current is sent through the coils. In this case the material of the rotor might saturate. Then the suspension forces can not increase any further and the magnetic bearing will become unstable. This is of course not permitted.

3.2 The influence of the suspension on the propulsion

The influence of the suspension on the propulsion can be analyzed using eq. 1. For a given configuration like the SPU, the parameters outside the brackets can be replaced by a constant k , and eq. 1 can be written as

$$F_L = k \cdot \left(\frac{I_0 - \delta I}{S_0 + \delta z} + \frac{I_0 + \delta I}{S_0 - \delta z} \right). \qquad (2)$$

Quite clearly, two parameters in eq. 2 are of importance in the amount of interaction. These two parameters are

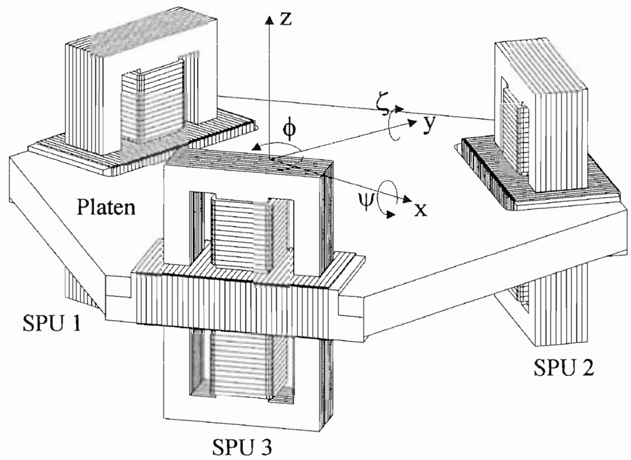

Fig.4: Layout of the six degrees of freedom, magnetically suspended and propelled platen. Three SPU's are used. The sensor system is not depicted.

δI and δz. If the magnetic bearing functions perfectly, then $\delta z = 0$, and the influence of δI will be canceled out completely. If this is not the case however, and δI changes slightly, then changes in δI will be of influence. The theoretical analysis of this effect can be found in [8, pp. 66-68].

An experimental set-up was built in order to measure the propulsion force and to analyze whether the suspension would be influenced by the propulsion. Measurements on the experimental set-up showed that δz will vary about 2 μm at maximum (with a nominal air-gap S_0 of 1 mm) during normal operation, and that δI will vary up to one percent of I_0. Assuming these variations as errors, eq. 2 shows that the relative error during normal operation equals 24 ppm.

4 Control

The control of the SPU can be done with a simple Lead-Lag control algorithm. When, however, a useful set-up is built, like the $XY\Phi$ manipulator described below, multiple input and multiple output (short: MIMO) control is needed. The most flexible way to control the system is with a digital controller. Using a DSP system based on the TEXAS INSTRUMENTS TMS320C40 processor from DSPACE, a Modal control scheme was implemented that worked quite satisfactorily [6].

5 Experimental set-up

5.1 Description $XY\Phi$ tables

At the Laboratory for Micro Engineering two experimental set-ups were built especially dedicated for research on the usefulness of the SPU for precision positioning. The experimental set-ups are both $XY\Phi$ manipulators, but one is a scaled down version of the other.

Figure 4 shows that three SPU's are used to support and to propel a platen. The platen has three iron rotors with secondary coils on it. The rotors are larger than the stators of the SPU's. This way a maximum travel of 10 mm in both the X and the Y direction is achieved. The dimensions of the E-core electromagnets are 60 mm x 40 mm x 20 mm. The platen is made of aluminum and is shaped the way shown in figure 4. The thickness of the platen is 20 mm and its mass including the rotors is 3.07 kg. The rotor dimensions are 80 mm x 20 mm x 40 mm. The air-gap is 1 mm. The three rotors are placed in the aluminum platen in a triangular configuration, at a center distance of 374 mm relative to each other.

An overview of the main specifications of the largest $XY\Phi$ manipulator is given in table 1. The smallest $XY\Phi$ manipulator has the same specifications, except that the strokes are halved.

5.2 Sensor system layout

For the experimental set-up three types of sensors are used. Eddy current sensors are used for the suspension function, and both capacitive sensors and a HEIDENHAIN incremental optical encoder are used for the positioning in the $XY\Phi$ plane.

The eddy current sensors chosen are commercially available from EPRO. They perform well for magnetic bearings. The stroke of the sensors is 2 mm, with a position accuracy of 1 μm. The signal to noise ratio is 72 dB, allowing for sub-micrometer position stability.

Originally, a set of capacitance sensors was used for the $XY\Phi$ positioning of the platen. The signal-to-noise-ratio was only 40 dB, thus allowing a bandwidth of the propulsion system of approximately 10 Hz.

At a later stage, a HEIDENHAIN PP109R incremental optical encoder was used for XY-position measurements. This sensor system allowed a bandwidth of 100 Hz with a signal-to-noise-ratio of more than 80 dB.

Suspension bandwidth:	100	Hz
Propulsion bandwidth (X, Y):	95	Hz
Propulsion bandwidth (Φ):	10	Hz
Suspension stiffness:	$4 \cdot 10^6$	N/m
Propulsion stiffness (X, Y):	$1 \cdot 10^6$	N/m
Propulsion stiffness (Φ):	$1 \cdot 10^4$	N·m/rad
Overall damping β:	$\frac{1}{2}\sqrt{2}$	-
Steady state error(X, Y):	30	μm
Range in X, Y:	10	mm
Range in Φ:	80	mrad
Range in Z:	1	mm
Range in Ψ,Θ:	4	mrad

Table 1: Specifications of the largest $XY\Phi$ manipulator.

6 Measurement results

6.1 Suspension results

The measurement results for the bearing direction are better (higher stiffness and bandwidth) than the measurement results for the propulsion direction [6]. Both set-ups show a very robust behavior. The large set-up has a load capacity of 3 kg.

6.2 Propulsion results

Several experiments were performed on both experimental set-ups in order to measure the performance for the set-ups. The measurement results concern: position accuracy, bandwidth, stiffness and correctness of the model used. One specific measurement that can be done to achieve very valuable information is a measurement of a step response. For the propulsion direction X of the large $XY\Phi$ table this is shown in figure 5. Figure 5 shows a damped vibration with a frequency of 10 Hz. This vibration is caused by cross-talk between the X direction and the Φ direction.

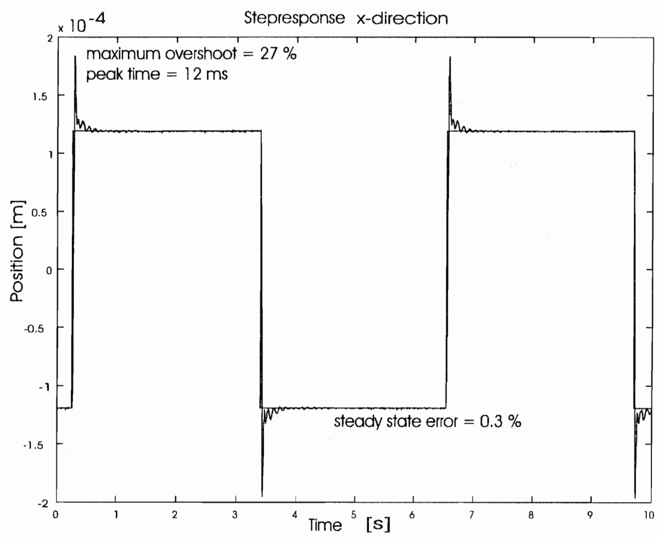

Fig.5: Measured step response in the X direction. This measurement is performed with the optical HEIDENHAIN PP109R incremental position encoder.

A bandwidth of 95 Hz has been achieved, together with a steady state error of 0.3 % of the step size. With a step of 10 mm, this error equals 30 μm. This is worse than expected and better control algorithms must be used to improve this. If, however, the noise level is inspected more closely, one can conclude that the position noise of the sensor allows for a 0.2 μm position accuracy. This is top-top sensor noise. The platen itself moves less. Extra research has shown [9] that a position accuracy of 5 nm can be achieved with the applied magnetic reluctance actuators. Trying to obtain a higher bandwidth was aborted, for the sensor noise started to dominate the response.

Figure 6 shows a bode plot of the open loop position in the propulsion direction Y. The theory predicted

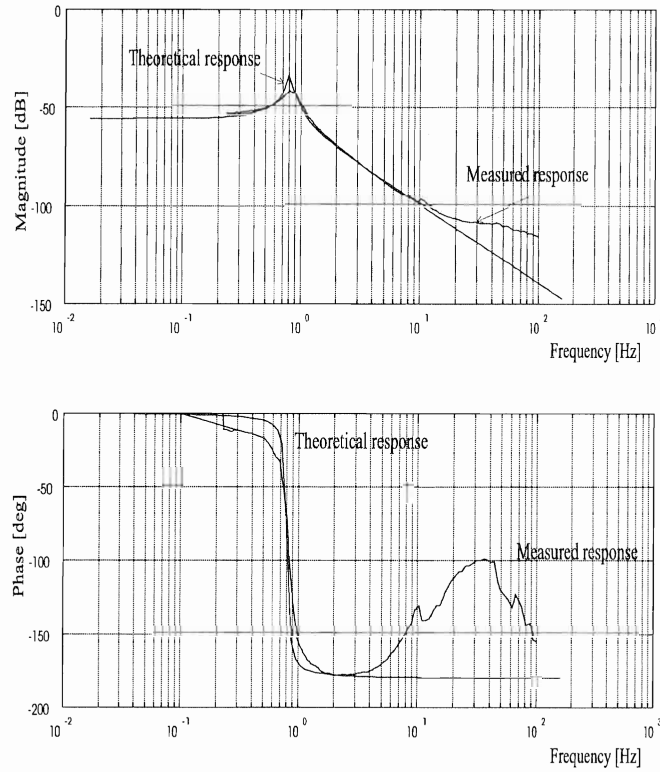

Fig.6: Bode plot of the process transfer function in the Y direction of the large table. The damped second order model (Theoretical response) shows a good resemblance with the actual performance measured (Measured response).

a double integrator (Lorentz actuator), but the graph quite clearly shows a second order system characteristic [8, p. 65]. This phenomenon was not yet explained completely, and will be a topic for future research.

7 Conclusions and future work

A function element has been built by the Laboratory for Micro Engineering that shows submicrometer accuracy in both the suspension and the propulsion direction. The $XY\Phi$ manipulator presented are a very good example of useful systems that can be built with the SPU. Both long and short stroke applications were researched and proved to work according to the theory.

Future developments will stay focused on practical applications with submicrometer accuracy and long stroke. For a better noise reduction the stiffness has to be increased. Therefore utilization of another coil configuration will be researched, combined with sensor performance improvement. The use of permanent magnets will be researched for the purpose of heat reduction. In order to apply the SPU in the future sucsesfully for precision positioning systems, both the range and propulsion force in X, Y and Φ direction have to be increased, in order to achieve high accelerations. For this, alternative designs have been set-up [10].

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