A NOVEL LOW DISSIPATION LONG STROKE PLANAR MAGNETIC SUSPENSION AND PROPULSION STAGE

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ABSTRACT

This paper presents a novel *Planar Active Magnetic Bearing* [PAMB] set-up implying reluctance forces for accurate vertical bearing or suspension and integrated Lorentz force type linear motors for fast propulsion in the XYΦ-plane. The principle joins power economic performance, submicrometer positioning and, in principal, unlimited long planar strokes.

The paper will deal with all aspects of the design, including the working principle, the dimensioning of the magnetic circuitry, the mechanical design and the controller aspects. Results will be presented of experiments on the first prototype, which is capable of handling an XY stroke of 160 mm × 160 mm.

First, the project's motivation is treated together with its history and approach. Then, the development of the novel bearing/motor combination principle is cleared by design considerations and (tested) improvements [1].

MOTIVATION, HISTORY AND APPROACH

In the 1980's, prof.D. Trumper started researching application of active magnetic bearings [AMBs] in the field of precision engineering. Thanks to advances in rapid controller prototyping equipment and integrated planar motor/bearing designs, *linear* AMBs are expected to become a common construction element for several high precision applications. These applications might favor from the advantages like contactless operation (no wear, no maintenance, applicability in Ultra High Vacuum [UHV], absence of stick-slip), and adjustable bearing characteristics (stiffness and damping; active vibration isolation). Disadvantages that could change this course of events are the high development costs, the limited dynamic stiffness and bearing force with its accompanying break-through risk, and the heat development by the coils.

The Magnetic Bearing Project at the Laboratory for Micro Engineering started in 1991 with a PHD research by F. Auer who designed a two Degrees-of-Freedom [DOF] bearing unit combining contactless Suspension and Propulsion [SPU], see figure 1. Prototypes showed very low mutual interaction/cross-coupling between suspension and propulsion,

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and sensor-limited accuracy (Auer, 1995; Auer and van Beek, 1994). Application of 3 SPUs led to an XYΦ positioning table with (only) 10 mm × 10 mm stroke in the horizontal plane, a dynamical stiffness of 4 N/μm, 0.72 N maximum propulsion force on a platen of 3 kg, a *relative* accuracy of one micrometer in all directions, and 86 W power dissipation during suspension.

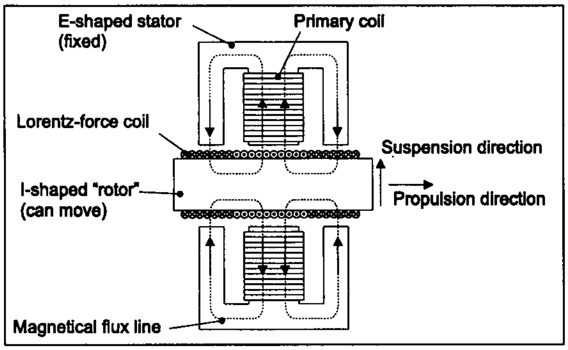

Figure 1: Principle of the Suspension and Propulsion Unit [SPU] developed by Auer, combining active magnetic suspension (primary coil) with direct Lorentz propulsion (secondary coil) (Auer, 1995).

This project is continued by the first author in June 1995. The goal was: development of practically applicable configurations of linear AMB in the field of precision engineering[2]. A market research for positioning tables revealed possible applications like specimen tables for observation underneath light optical microscopes, and fabrication of micro-systems by Micro Electro Discharge Machining (Micro-EDM); both suit the limited (dynamical) stiffness of AMBs. But, these applications are already served by high-end systems on air-bearings. Therefor, a magnetically beared system must be cheaper—which seems feasible since no accurately machined parts are needed—or has to offer additional features like adjustment of height.

The price of the 6DoF controller (including sensors and amplifiers) will be a dominant factor, but electronics are becoming cheaper. If, on the other hand, the generation of heat is decreased, an AMB type of positioning device might become an alternative for vacuum applications e.g. specimen tables for particle optics. For application in UHV the development of heat should be minimized, and the power dissipation on the suspended object needs to be negligible.

Comparison of these demands with the existing 3SPU XYΦ table, leads to the conclusion that improvement of (planar) stroke, accuracy, propulsion force, and thermal management is necessary. This can only be accomplished by a thorough re-design or a completely new principle. The next section will treat the approach followed towards such a novel mechatronically designed bearing-motor combination.

DEVELOPMENT OF A NOVEL PLANAR MAGNETIC BEARING CONFIGURATION

To come to an improved magnetically beared linear motion table, magnetic forces and configurations for suspension and propulsion are evaluated in the next paragraph. Then, design considerations are treated, together with suggested improvements of which some were validated by test set-ups. Finally, this leads to a novel planar magnetic configuration.

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[2] Throughout this article, the following definitions are used:

bearing confinement of one or more *linear or rotational* Degrees-of-Freedom [DoF]

suspension or levitation stable vertical hovering *and* positioning e.g. by a (vertical) bearing

motor or propulsion linear or planar drive of unconfined DoF

stage the part that is suspended (between the stator), in literature sometimes referred to as (non rotating) rotor or flotor

MAGNETIC FORCES AND CONFIGURATIONS

Planar suspension ... Most magnetic suspension approaches for contactless 6DoF operation are based on reluctance force for its high power-weight ratio and low dissipation. A reluctance force is characterized by an effective working distance of several millimeters only, which is sufficient for gravity compensation—still allowing some z-adjustment. Straightforward application of six actuators leads to fine- or sub-stages with small stroke (Trumper and Queen, 1991; Benoit, Erni, Rochat, Bleuler and Müller, 1996).

Extension of the iron targets in one direction gives a straight motion system—a linear reluctance motor (Müller, Andreasch, Bleuler, Kawakatsu, Rupp and Schwab, 1996; Kuzin, 1994) or a DC motor (Schwarz and Trumper, 1996; Holmes, Hocken and Trumper, 1996; Auer, 1995) can be integrated.

Difficulties arise when planar motion is to be achieved. Firstly, stacking several linear systems is impossible with AMB slides because of their limited stiffness and limited force. Secondly, general reluctance actuators (like the SPU) either have a limited stroke or a heavy suspended iron target, and, hence, a small propulsion force-to-mass ratio.

... **and propulsion** ... There exist several alternatives to Lorentz propulsion that are contactless too (Bleuler, 1992). These are based on a reluctance force (= attracting poles—originating from the potential energy of the field) or an induction force (= Lorentz force by eddy-currents = electrodynamical force).

The disadvantage of reluctance force for propulsion is that it demands a magnetically varying shape of the target: an array of alternating permanent magnetic or electromagnetic poles. Ferro-magnetic targets cause cogging, but coreless coils can be applied too. Still, common AMB actuators need a large target area on either the stator or the platen to obtain substantial perpendicular freedom of motion.

The disadvantage of inductive force is that it is either slow (minimal dissipation control) or power inefficient (field oriented control: about 12 W/N). Therefor, the inductive force is not considered as an alternative for both suspension and propulsion.

... **combined** When propulsion is added to a suspended platen, the most straightforward way is to add a separate DC motor. But the permanent magnets [PM] inside such a motor cause a strong pre-stress force commonly counterbalanced by conventional ball- or air bearings. When magnetic bearings are applied for suspension, this force needs to be part of the design for two reasons.

Firstly, the expected variation of platen height imposes a certain amount of ampere-turns for compensation to be available. With a PM array this can be a lot. Secondly, the negative stiffness of this pre-stress behaves like a bias flux causing high demands on the control-system, which needs to compensate this characteristic into a positive stiffness by fast proportional action. Choosing a double-sided motor configuration instead of a single sided one does not compensate for this.

It is therefor concluded that an integrated combination of motor and magnetic bearing principally offers the highest propulsion force possible without destabilizing the bearing. Apart from the SPU, only two configurations known to the authors agree with this philosophy: the linear motor/bearing by D. Trumper's group (Kim, Trumper and Bryan, 1997) and Kuzin's bearing/reluctance motor.

Kim applies coreless coils that suspend a PM array (in Halbach configuration) by repulsion. Leaving out the back iron omits the disrupting attractive force but cuts back efficiency. The coils generate too much heat for vacuum application. Kim recommends application of superconductive coils which is too complex for our research project.

Kuzin's design seems potent, but the integrated reluctance motor is expected to cause cogging and cross-couple with the suspension force. No experimental results are known to the authors.

Conclusion We therefor conclude that an SPU type of combined suspension and propulsion seems favorable—but some aspects like power dissipation and stroke need improvement.

Permanent magnet biasing The main advantage in using PMs is the higher bias-flux which can be obtained with much less power dissipation by the suspension coils. Hence, application of PMs yields a higher propulsion force then possible with the SPU set-up that uses EMs. Based on existing rotation bearing designs a so called non-coplanar configuration was chosen (Sortore, Allaire, Maslen, Humphris and Studer, 1990; Trumper, Kim and Williams, 1994; Lee, Hsiao and Ko, 1994). A test set-up was built—called the Non-Coplanar Suspension Unit [NCSU]—with which power dissipation decreased to below 1 W while fluxdensity increased 5–20 times compared to the SPU (Molenaar, van Beek and Sanders, 1997).

Long stroke The combination of the NCSU and the SPU has lead to the concept of a new planar magnetic bearing actuator principle, offering inherently long strokes and direct Lorentz propulsion by *crossing flux-guidance bars.* This will be explained in the next section.

PRINCIPLE OF THE NOVEL MAGNETIC CONFIGURATION

Suspension The magnetic bearing force needed to compensate gravity is based on reluctance forces, generated mainly by permanent magnets (*suspension*). Long strokes perpendicular to the direction of gravity can be achieved by a new method of crossing flux-guidance bars[3]. In figure 2 the basic configuration is shown with the parallel flux-paths of permanent magnets (PMs) and electromagnets (EMs), which are comparable to the NCSU.

The suspended part is light weighted related to the long planar strokes that can be made. Because the overlapping area is constant, the bias flux is independent on the planar platen position by high approximation. Therefore, the load capacity and propulsion motor-constant are invariant and the control of both might be simple.

The magnetic induction in the airgaps is created by the PMs through the flux-guidance bars, similar to the SPU in figure 1. To vary this induction, and, hence, the reluctance force needed for suspension, a so called control-flux is generated by the coils at the stator ends—efficiently coupled through the remainder of the flux-guidance bars.

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[3] International patent pending.

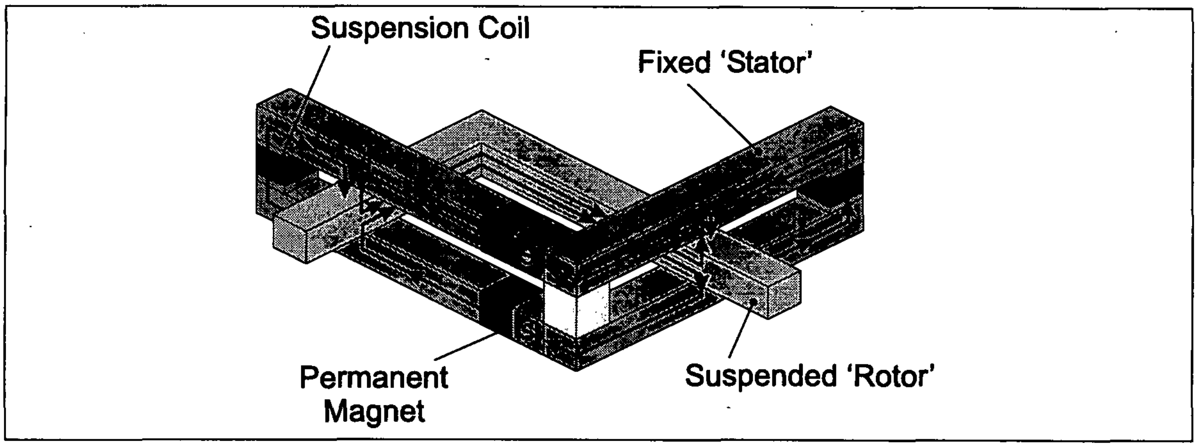


Figure 2: The novel planar magnetic suspension configuration, showing permanent magnets (for bias flux) and electro-magnets (for control) with parallel flux paths. By crossing flux-guidance bars, a long stroke can be achieved at a small suspended mass. Propulsion force can be added likewise the SPU—see figure 1.

Propulsion The platen is *propelled* by Lorentz forces—generated by coils wound around the suspended part. The ampere-turns from the Lorentz force coils must pass the high reluctance of the PMs. Hence, the high reluctance of the PMs (with $\mu_r \approx 1.4$) block possible cross-coupling to the bearing function and assure a low inductive load on the amplifiers, independent of gap-position. The homopolar yoke makes commutation unnecessary.

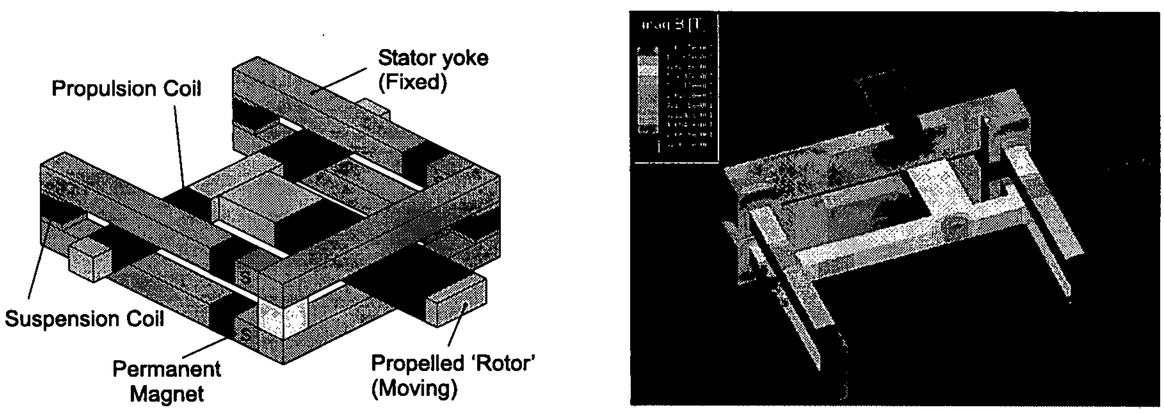
DESIGN CONSIDERATIONS

Dissipation Since the bias flux for both suspension and propulsion is provided by PMs, the power dissipation is low compared to a set-up that uses EMs like the SPU. At a proper platen height within the air-gap, the bias flux from the PMs can fully compensate for the static gravity, leaving the dynamic disturbance cancellation for the control coil. The calculated dissipation during suspension is at the milli-Watts level. This enables application in UHV.

Depending on the duty cycle of the propulsion task, the dissipation of the secondary coils is still several Watts. But, by disconnecting momentarily unused secondary coil-segments, power dissipation can be reduced.

Magnetic hysteresis of yoke parts can causes energy dissipation. For the suspended yoke part, this can be troublesome in vacuum. But, since the yoke is homopolar, losses are principally low, since the inductance varies within one quadrant of the BH curve.

Controllability From the control point of view, there are three good characteristics of the SPU that are carried by this configuration. First, suspension and propulsion forces are perpendicular. Second, both have the same origin of force, preventing bending of the suspended object and hence vibrations. Third, the vertical stroke within the air-gap of the bearing is limited by the coils needed for propulsion. This limits the change in bearing flux—hence ampere-turns—which needs to be compensated by the primary coils at startup.



(a) The components of the magnetic circuit of the test set-up, showing three of the five secondary Lorentz-force coils needed for planar propulsion in the horizontal XYΦ plane.

(b) The magnetic induction as calculated with 3D Finite Element Analysis. On the suspended object, a residual force was calculated of 0.3 N, pointing towards the corners of the U.

Figure 3: The planar active magnetic bearing (PAMB) test set-up.

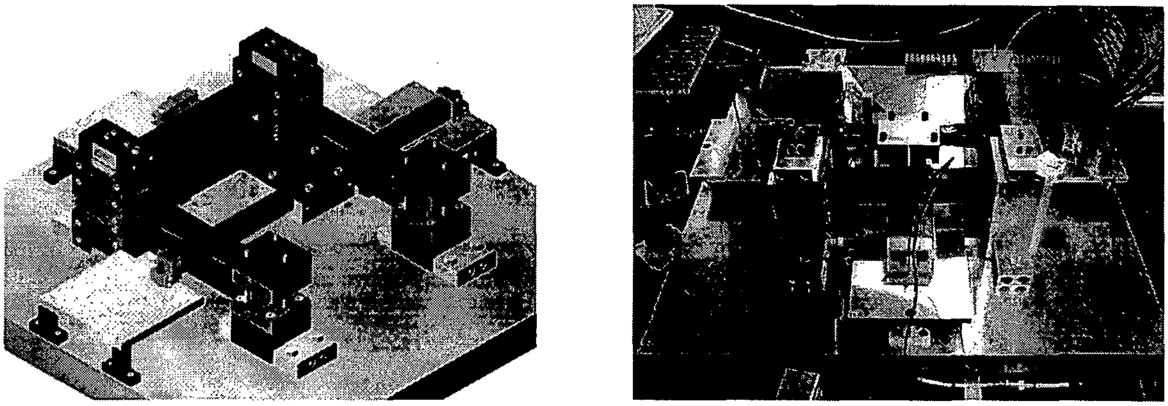
PAMB SET-UP: DESIGN & DIMENSIONING

Planar configuration Many configurations are possible with this principle by alteration of the basic double-L shape. The basic LL configuration (figure f:pambhalf) can control two vertical DoF with the primary coils and maximally three planar DoF by stacked coils around the platen. For a planar stage, one needs to combine two basic configurations with the disadvantage of four bearing positions of the suspended object. To prevent this, three bearing positions can be made by merging two poles.

The UT configuration, as shown in figure 3(a), was chosen for a test set-up: the novel 160 mm × 160 mm planar active magnetic bearing called PAMB. Apart from the secondary coils depicted in figure 3(a), an additional set of thin coils is wound around the long 'arms' of the T to control the rotation around the vertical axis. For this, the T was split along its 'body'. See figure 4(b).

Magnetic circuit dimensioning The *dimensioning* of the magnetic circuitry was done analytically, and verified by 3D magnetic finite element analysis, as shown in figure 3(b). By a smart choice of cross-sectional areas of the yoke parts, the bias flux (= magnetic pre-stress for force-current linearization) of the circuit was made self-adjusting to the optimal value of 50% (Lee et al., 1994). So, when the permanent magnets are chosen (slightly) larger, the excess of magnetic field strength is lost by stray flux automatically.

From figure 3(b) one can verify that the magnetic induction in the air-gap is about 1 T while the stator-parts between control coils and air-gap are well below saturation at about 0.5 T. Consequently, the suspension force can be changed from say F to zero or 2F when the induction in the air-gaps is varied from zero to 1.4 T, respectively. The



(a) Drawing of the mechanical lay-out of the experimental set-up, showing the yoke parts, support frame and square target planes for the eddy-current sensors. The base plate measures 500 mm squared.

(b) Photograph of the top of the PAMB experimental set-up showing the fixed double U-shaped yoke, the suspended T-shaped part, and the three eddy-current sensors which are mounted at the ends of the T (wires are visible) and are pointed towards the square aluminum targets.

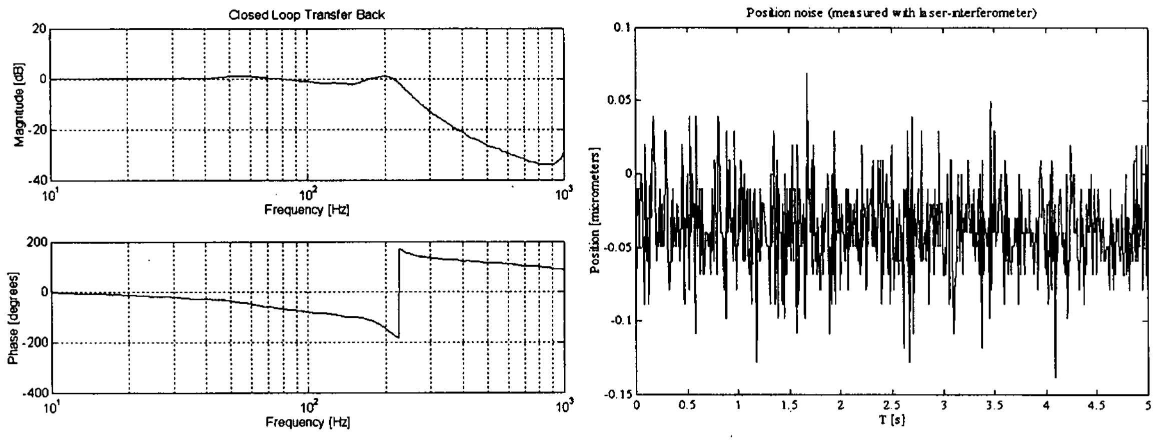
Figure 4: The PAMB test set-up.

suspended yoke and remaining parts of the stator-sides are close to saturation, assuring optimal usage of the yoke material. The stator's back-side is doubled to prevent stray from the PMs and to make it possible to use a twice as large control coil at one corner only. Then the other side can be a non-ferromagnetic (e.g. aluminum) support block, decreasing coil inductance. A coil at both sides is feasible, though. Then, two opposing fluxes are applied, forcing the flux through the air-gaps and the platen.

The PM were made of NdFeB, sized 42 mm × 42 mm × 10 mm. The six air-gaps are 1.1 mm in height. The general cross-sectional area of the yoke parts was chosen 20 mm x 20 mm, leaving space to 45 secondary windings for one layer between the gap; diameter 0.4 mm with I_{max}=2 A. Hence, with 1 T magnetic induction the expected propulsion force is 7.2 N. Since the mass is 3.37 kg, this gives a maximal acceleration of 2.1 ms^{-2} in the two perpendicular directions of the secondary coils (even higher at angles in between). The stiffness of one pole is $-1.5 \cdot 10^5 \frac{N}{m}$, while the 75 primary windings deliver 20 $\frac{N}{A}$.

Mechanical set-up The mechanical design was optimized for both a stiff construction—needed to achieve a high lowest eigenfrequency and hence a high controlled bandwidth and dynamical stiffness—as well as a long stroke for the center of the platen, as shown in figure 4(a).

All yoke parts are made from laminated transformer steel. Possible vibration of the laminated parts was researched by means of finite element calculation and some experiments. It was shown that these vibrations are even smaller than for massive iron rods provided that the glue adheres well.



(a) Bode plot of the closed loop transfer function.

(b) Position noise 0.22 μm peak-peak

Figure 5: Measurement results of the PAMB.

Sensor configuration For the vertical position sensing three Kaman eddy-current sensors are mounted at the platen ends. See figure 4(a) and 4(b). An experimental incremental encoder system measuring three strokes of 100 mm × 100 mm × 3° will be implemented (as used by (Kovalev, Gorbatenko, Saffert, Schäffel and Kallenbach, 1996)).

Controller For the results presented, a high stiffness was aimed for. A DSPACE TMS320-C40 digital control system is used. Sensor output is low-pass filtered at 1 kHz. Bipolar DC amplifiers were chosen (±50 V, ±2 A).

PAMB SET-UP: RESULTS

The platen is currently controlled by three decentralized PID controllers, showing a robust push-button startup behavior in spite of the severe non-colocation. A load of 5.8 kg can be suspended stably. About 130 mm × 130 mm stroke is achieved under stable, noise free operation. A bode plot of the closed loop transfer function at the back side of the T is depicted in figure 5(a).

The measured maximum continuous propulsion force is 6.7 N at I_{sec}= 2 A (10 $\frac{A}{m^2}$). This nicely matches the performance estimated. The secondary coils limit the vertical stroke to a clearance of several tens of a millimeter. Still, a 40 micron heightened platen-position can be set at a total power dissipation in the three primary coils of 0.3 mW only, while the 3.37 kg platen is lifted. This originates from disturbance cancellation. The set-up stands on a regular lab table without vibration isolation.

CONTINUATION

Apart from the 100 mm × 100 mm position sensor, a position dependent state space controller needs to be implemented on the PAMB. For large strokes, the arms of the three suspension forces to the *center of mass* are changed. A position dependent state space controller can compensate for this. This, or a colocated sensor configuration, seems inevitable for obtaining the demanded absolute accuracy of one micron on a 6DOF controlled set-up. Z-domain and analogue control are considered to improve the bandwidth.

Optimization of combined propulsion and suspension is further researched through a mathematical description of all reluctances, including stray. Optimal dynamics and compactness can be reached for specific applications like a stepping or a scanning motion. Then, a proper choice of bias flux, air-gap height and pole face area can lead to a higher force-slew-rate and propulsion force.

CONCLUSIONS

A novel planar active magnetic bearing actuator principle has been developed from which numerous basic shapes and long stroke actuators can be derived. All suggested systems combine three, long stroke, DOF with direct propulsion, unipolar magnetic circuits and milli-Watts power consumption for suspension.

Preliminary results of a first prototype—the PAMB—prove the feasibility of the concept by showing a robust behavior. Most advantages of the previous SPU are maintained, while the planar stroke has been enlarged 16 × 16 times and the dissipation during suspension is decreased from 84 W to 0.3 mW. A propulsion of 0.2 g can be reached at 12 W dissipation in the platen-coil. Both values can be improved a factor five at least by addition of windings and switching of coil segments, respectively.

The motor/bearing principle presented shares one disadvantage with the SPU: heat dissipation by propulsion coils on the platen complicate application in UHV.

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