MAG-6D A NEW MECHATRONICS DESIGN OF A LEVITATION STAGE WITH NANOMETER RESOLUTION

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INTRUDUCTION

Magnetically levitated positioning stages have been very familiar since the 90s, and extremely accurate systems are used in semiconductor industry for fine positioning of wafers. [1] [2] The main advantage in relation to “standard” air bearing systems or mechanical guided systems is that magnetic levitation provides perfect cleanroom conditions. The other advantage is that the precision of the position and trajectory motion only depends on the sensor performance and the control capability - there is no influence on inaccurate guiding - because there is no additional guiding.

Industrial applications require free access to the top plate of movable platform, which carries the probe for handling operations. Therefore, all measurement systems have to be installed on the bottom or on the side. Most of the high-resolution laser interferometers, confocal measurement systems etc. are so expensive that a system design with those types of measuring tools is possible but not relevant for certain industrial applications because of the acceptable end user price level.

We are looking for a system design that overcomes the bottleneck at the sensor arrangement and brings the price level to less than the price of standard stacked nanometer positioning systems.

The paper describes a new magnetic levitation system with nanometer resolution, a passive platform with focus on a cost-effective sensor and driver design. It enables use in several high-precision positioning tasks in 6 DOF (degrees of freedom).

The system combines a fully passive stage with 8 Halbach arrays and an optical sensor grid. The optical incremental sensor grid is placed onto the movable stage between the magnetic arrays and the coil board, which is placed on a granite baseplate. 7 optical incremental sensors heads, and additional analog hall sensors are fixed on the light-weight granite base.

MAG-6D NEW CONCEPT

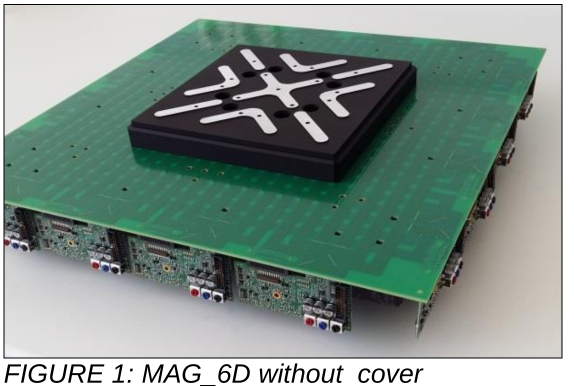

FIGURE 1: MAG_6D without cover

Figure 1 shows the MAG_6D system without cover, the power and sensor-data cables. The passive stage carries the Halbach arrays and a 2-D grid. All drivers are mounted in connectors directly on the PCB.

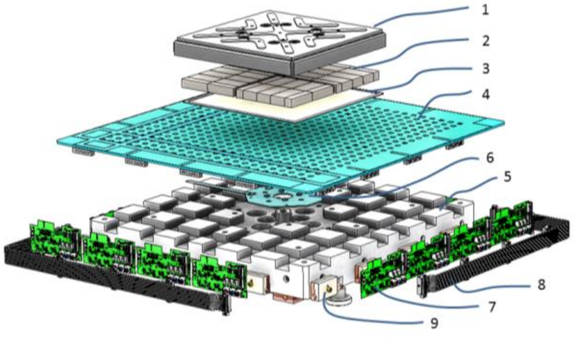

FIGURE 2: Assembly of the MAG_6D

1 Movable stage
2 Halbach array (consist of 8 arrays)
3 2D optical grid
4 Coil board (PCB with 144 coils)
5 Granite baseplate (nonmagnetic)
6 Sensor module with 7 sensor heads
7 Current drivers (48 full bridges)
8 Cable set-up and sensor connector modules
9 Heat pipe for very low thermal hot spots

8 Halbach arrays are placed in two pairs on each corner and rectangularly in two pairs.

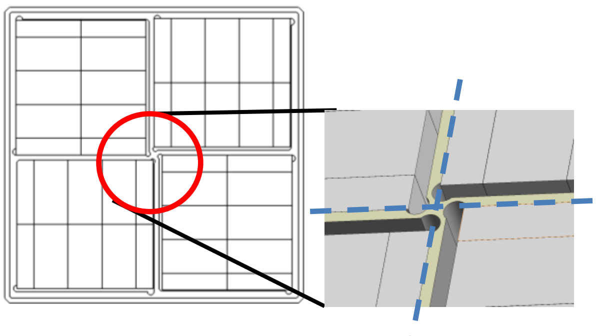

FIGURE 3: View of the bottom side of the stage (the 2-D optical grid is removed)

2-D OPTICAL GRID

Metal bridges with a thickness of a few millimeters are placed around each Halbach array pair to support the 2-D optical grid. The 2-D optical grid consists of a hardened glass substrate with chromium dots and has a thickness of 0.7mm. This special glass substrate together with the suspended metal bridges keeps the grid surface reference flatness at less than 4 µm ripple. The surface will be mapped into the Z sensor control matrix with about 2000 points. In our formal magnetic levitation design [4], the magnetic structure was mapped into about 10000 data points and was also used for on-the-fly error correction in the control algorithm.

HALBACH ARRAYS WITH LARGE PERIODS

The force calculation is done with a combination of FEM magnetic field methods, a Lua script based on Python and a newly designed, fully graphical software interface. Fig.4 shows the good correspondence of the calculated magnetic field components to the measured field distribution. Symmetrically Halbach arrays are chosen for generation of the strong magnetic field. To reduce the weight of the movable stage, the thickness of the Halbach arrays was halved. That reduces the weight by a factor of two but reduces the field in the board layer only by a factor of 1.3. The 3-D field magnetic measuring technology based on an “F3A Magnetic Transducer” - a 3-D magnetic Hall probe - from SENIS. [3]. For the scan operation, our high-precision positioning technology synchronized with PI’s hexapod controllers and a proprietary GUI program tool is used.

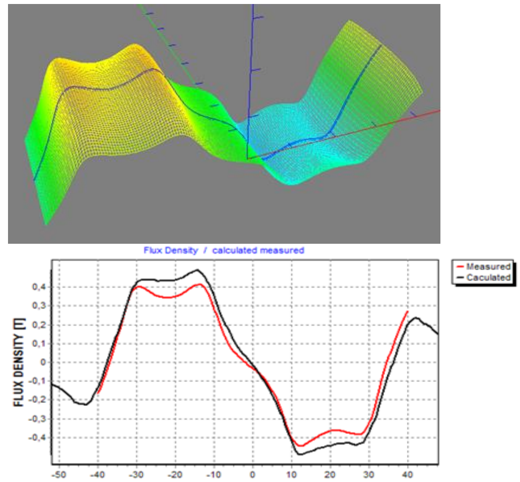

FIGURE 4:
One segment of the 8 Halbach arrays, period of 42 mm a) 3-D - measured magnetic flux density in a horizontal direction (X); the blue line shows the cross section for 2-D b) 2-D - verification between measurement and simulation shows acceptable conformity

COIL DESIGN

Coil design with mechanical gaps between the electrical phases. These gaps are used for fixation of the board and for accessing the sensor heads through the board onto the 2-D optical grid.

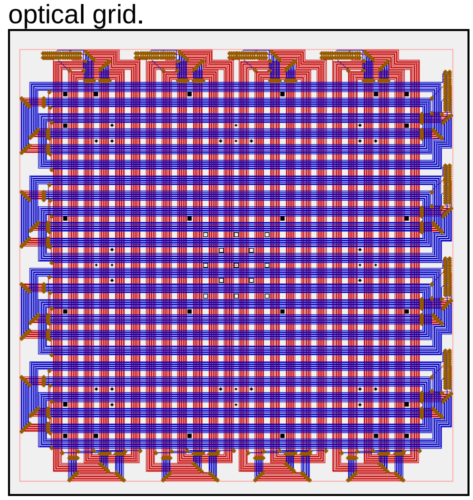

FIGURE 5: One layer of the PCB with the 144 coils

The coils are placed rectangularly onto the upper and lower side of this single layer, buried vias are used to allow the cross section of the coil structure. Each horizontal and vertical coil is connected to a connection area where the connecting point shifts in each layer to the next pin section on the current driver connector.

The coils inside the PCB are placed at gaps of 5 mm. Some of the gaps have rectangular holes through the PCB to open the light path for the incremental optical sensor heads. The stage design is optimized for high electromagnetic forces. The static lifting force (Z direction) is more than 4 times the weight of the stage and can overcome 6 times this value for dynamic operations. This is much higher than in our former design with the six-coil structure. [4]

With a moderate current of only 1.5A in the clusters of the coil assembly, the stage can be driven by more than 40 N in a vertical and horizontal direction. The coil structure (in 12 layers on a PCB) does not need additional wiring and is connected with highly efficient PWM drivers, placed directly on the main board. The drivers are controlled by digital serial SPI channels – the digital connection to the controller.

The 48 full bridge drivers have a very efficient design and this reduces the risk of EMI distortions, because of the short connection to the board, the high PWM frequency, and a simple filter function. The PWM frequency is set to 400 kHz and is synchronized between the boards.

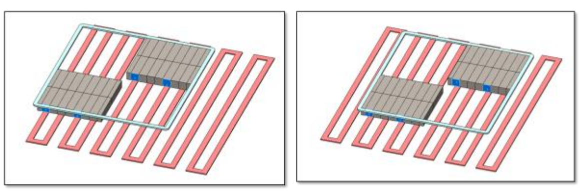

FIGURE 6: Tolerances on Halbach arrays have no influence on the forces generated at different X-Y positions. (Was already discussed in earlier paper by X.Lu et al.)

Maglev systems with PCB coils are already familiar in the literature, but these systems need measuring sensors which span over the upper working surface of the movable stage. In that case, the stage can't be used in industrial applications where the upper surface has to be free for the customer scanning application. [5] In our new design, the platform surface is free. The coils inside the PCB are placed at gaps of 5 mm. We could also see that the efficiency of the Halbach array design is better than in a configuration with three long Halbach elements.

Some of the gaps in the coil board have rectangular or cylinder holes through the PCB to open the light path for the incremental optical sensor heads and for additional hall sensors for the initialization procedure. The system uses a set of 4 incremental sensor heads separated by 28 mm, placed in 4 of the small gaps on the main PCB board. The small sensor heads are assembled on 4mm rectangular piggy-back boards to get the designated height. The sensor noise was determined to less than 8nm (RMS).

GRANIT BASE PLATE

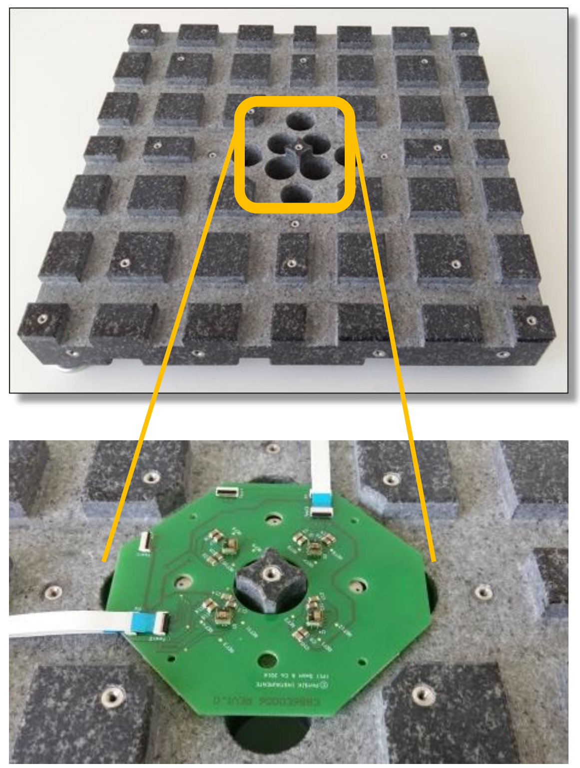

FIGURE 7: implementation of the 7-head sensor module, 4 optical incremental sensor heads and 3 interferometer distance heads

Nonmagnetic granite was chosen for the baseplate. The PCB and the sensor modules are fixed in nonmagnetic inserts on the granite plate. Thermal conductive silicon is used between the PCB and the granite base plate; thermal conductive graphite was also tested. That layer of thermal conductive material reduces formation of ununique thermal zones on the PCB.

TEST RESULTS

To check the performance of the magnetic structure, the 3 phase coils and the drivers, a number of magnetic distrubution measurements are done with high-resolution 3-D magnetic sensor chips from Austria Microsystems.

The following measurement results show high consistency between the desired magnetic distribution of the flux density on the coil level between the computer simulation and measurement. It is an overall test including controller functions.

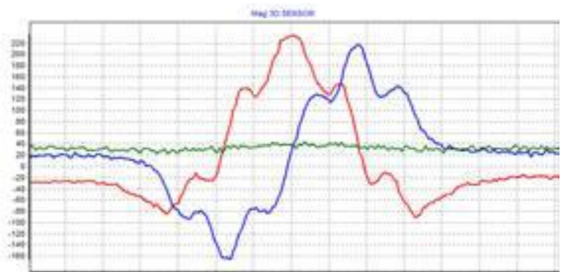

FIGURE 8a: Measurement of flux density 2 mm over the coil level (PCB) for "3-phase lifting current condition"

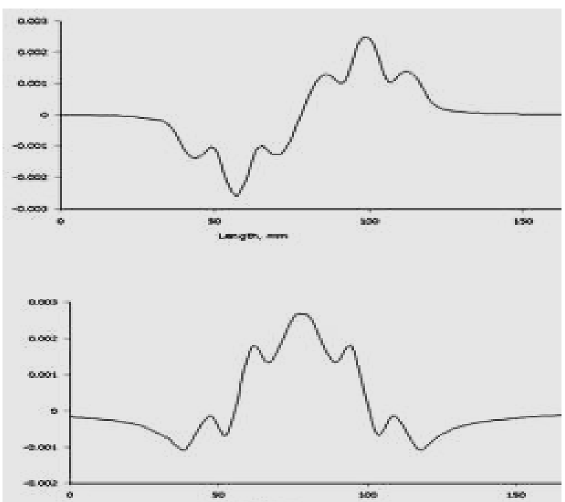

FIGURE 8b: Computed flux density in normal and tangential direction, generated by the 3-phase coil current.

Because of the high PWM frequency of 400 kHz, we could use 6.8µH chokes with small dimensions for the low-pass filter function. The PWM ripple in the coil layer is smaller than 100mV.

DECOUPLING OF LIFTING AND X/Y FORCES

There is a 60-degree phase angle of spatial frequency between phase1_2 and between phase 2_3.

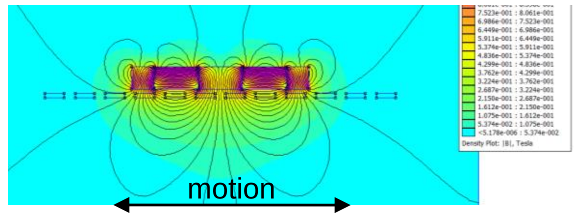

FIGURE 9: Flux simulation of one Halbach array

The spatial frequency current distribution for three phases of the coil structure can be defined as:

$$\text{ampl} := 1 \quad (1)$$

$$\text{phase1}(x) := \text{ampl}\cdot\cos\left(\pi\cdot\frac{x}{42} - \frac{\pi}{3}\right) \quad (2)$$

$$\text{phase2}(x) := \text{ampl}\cdot\cos\left(\pi\cdot\frac{x}{42}\right) \quad (3)$$

$$\text{phase3}(x) := \text{ampl}\cdot\cos\left(\pi\cdot\frac{x}{42} + \frac{\pi}{3}\right) \quad (4)$$

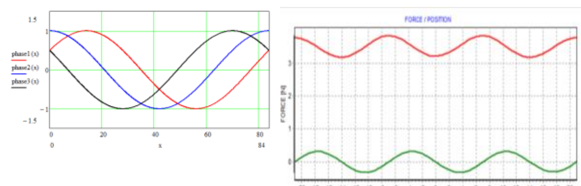

FIGURE 10a: Shows a 10% sinusoidal distortion of the lifting force and of the horizontal force component. (spatial frequencies)

$$\text{ampl}(x) := 1 + 0.09\cdot\cos\left(\pi\cdot\frac{x}{7}\right) \quad (5)$$

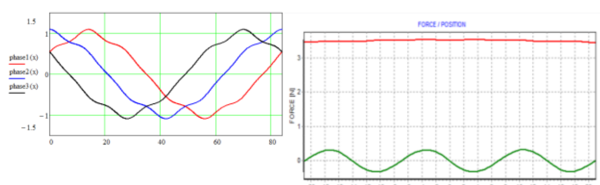

FIGURE 10b: The spatial frequency amplitude modulation (5) results in decoupling of the lifting force without influencing the other force component.

It can be shown that the horizontal component can be also decoupled and linearized by using a spatial frequency phase shift between two phases. With this feed forward term, the control function can be linearized despite the fact that the gaps in the coil structure distort the linear properties.

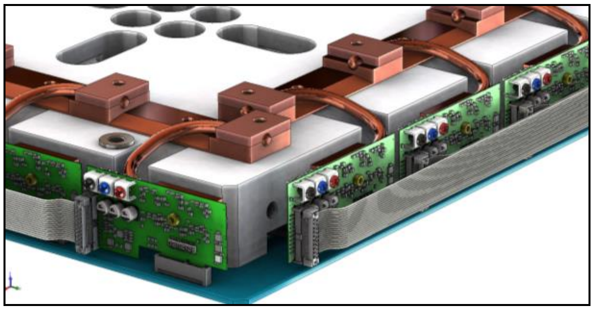

FIGURE 11: Bottom view of the stage, heat pipes between the current driver modules and the heat sinks on the granite base plate

Because the coil drivers are designed with highly effective PWM full bridges, there is moderate heat generation even without an air cooling stream. The heat generation is further reduced by using passive heat pipes.

CONTROLLER STRUCTURE

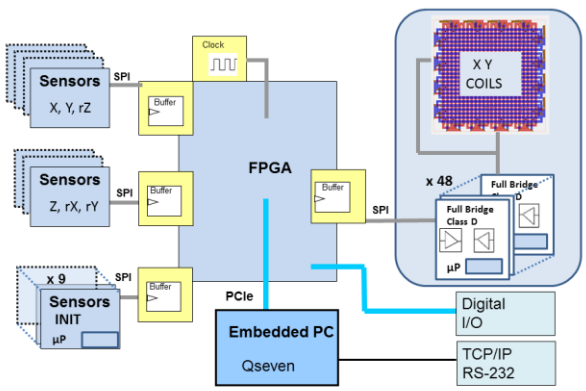

FIGURE 12: Controller structure

We chose a well-known structure for the controller.

- Digital channels for the 7 sensors + 9 ratiometric Hall sensors
- Driver close to the stage
- Power direct to the driver
- Digital-controlled channels (24) to the driver
- FPGA with crystal clock for all sensor interfaces
- Intel's PC processors (4 core) for high computing power, coupled with PCI express lanes and direct memory access
- Real-time operating system on the PC platform, 20kHz sample clock
- Option for 7" touch display

This design also opens the way for using the complete PI Software package. Command structure and trace functionality are available. The control commands are the same as those used for a 6-DOF piezo stage.

FURTHER WORK

At the time of publication, some components were not available in industrial product quality, so the controller consists of the target components but is not at the quality level of an industrial-proven model ready for shipping. We also made tests with different low-budget, high-resolution interferometric distance sensors for the short displacement of 4 mm using the same digital interface. Generally, the robustness of the new system has to be qualified and it is possible that particularly the Z sensors may need to be modified.

Although there is still some room for improvement of the magnetic field design and the control performance of the magnetic levitation system, the real challenge is choosing the right sensor systems for a low-budget mechatronics system.

SUMMARY

A new magnetic levitation system could be realized with a PCB-based coil structure with gaps between the phases and a 2-D grid that span over the bottom side of the movable stage. The new and very compact low-budget design of the MAG-6D system is scalable. This scalability issue allows adaption of the stage design to a number of planar positioning applications in industry and research.

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