6D planar magnetic levitation system – PIMag 6D

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Abstract

The paper describes the structure of a novel 6 DOF planar magnetic drive system with nanometer accuracy. Some details of the model based design are described and some performance and qualification results are given. A main advantage of the system is that it uses only six, i.e. the minimum number of sensors and coils to control all six degrees of freedom what keeps the system simple and makes it very effective. Furthermore the measurement system and the actuators are completely located below the slider; hence the platform is freely accessible from above and does not need any wiring connection since only passive parts as permanent magnets and grid plates are placed in the moved part of the platform.

Key words : 6 DOF nano positioning, Magnetic levitation, Planar magnetic bearing system, Halbach array, Thermal management, Feed forward based on correction matrices, Trajectory control

1. Structure of the system

The new developed magnetically levitated motion system with six degrees of freedom allows a motion of the slider-platform of $100 \times 100 \text{ mm}^2$ in x y direction and $100 \mu\text{m}$ in z direction. Rotation around z axis is limited by the measurement system to $\pm 0.25^\circ$, rotation around x and y axis is limited by the geometry of the system to $\pm 100 \mu\text{rad}$.

The system is actuated by 3 coil pairs mounted at the stator which interact with 3 Halbach arrays in the moving platform. Using only 3 linear magnet arrays instead of 4 (Ruben, et al., 2011), (Kim and Trumper, 1998) or a 2D Halbach array (Jansen, et al., 2008) minimizes the required components of the system. Furthermore a system with only 3 arrays is smaller and lighter what decreases the power losses and hence the thermal load of the system. The more elaborate commutation can easily be done by the controller. The use of efficient Halbach arrays gives high magnetic field components below the slider reducing the power consumption of the coils and hence the heat generation in the system. Temperature stability is an important requirement for high accurate positioning technology. The measurement system consist of a compact 6D-measuring head, placed in the center of the coil pairs and a moving grid plate mounted on the bottom side of the slider platform. The planar degrees of freedom (x, y, r_z) are measured by 3 optical sensors which scan the grid. The vertical degrees of freedom (z, r_x , r_y) are determined by 3 pairs of capacitive sensors, which measure the vertical distance to the grid plate. The sensor resolution is in the nanometer and tenth of micro radian range ($\Delta r_z = 0.25 \mu\text{rad}$; $\Delta r_{x,y} = 0.07 \mu\text{rad}$). A main advantage is the grid plate inside the movable platform. Therefore the sensor system allows the access to all sides of the platform, a requirement in inspection systems. Furthermore the moving platform is completely passive. No cables or other connections between slider and stator, which can introduce disturbance forces, are needed. To avoid disturbances on the capacitive sensor values the frequencies of the PWM amplifiers and the measurement frequency of the sensors are synchronized.

Fig. 1 Slider bottom side

Fig. 2 Schematic structure of the prototype system, with global Cartesian coordinate system

Fig. 3 Setup of the prototype system;
l x w x h: 50 x 45 x 14 cm³

2. Halbach array configuration and commutation

Halbach array configurations are known for their high flux density on one side and small stray fields on the opposite side. The high field components below the magnets minimize the power consumption of the coils. Due to that characteristic they were chosen for the setup. The $\text{Sm}_2\text{Co}_{17}$ -magnets with medium magnetization grade generate a flux density of about 0.5 T below the array. This material is also ultra-high vacuum compatible and can be used in applications that require a strong hydrogen atmosphere. Hence these magnets were used in a first prototype. Contrary to (Jansen, et al., 2009) and (Kremers, et al., 2013) no semi-analytical models but FEM calculation was used to determine the field of the magnets and their interaction with the coils.

Figure 4 shows a schematic of an array with a FEM result. Depending on the coil position with respect to the magnets coil currents generate horizontal and vertical forces. Additionally a torsional torque around an axis perpendicular to the image plane of Fig. 4 is generated.

Fig. 4 Model of a Halbach array (above) and flux distribution calculated by FEM (below); the sketch shows, how vertical and horizontal forces can be generated by a coil pair; dimensions of magnet: 11.4 mm x 11.4 mm; dimensions of coil element: 8.5 mm x 10.4 mm

Fig. 5 FEM-calculated position dependent forces and torques at a Halbach array, caused by the left (blue curves) and the right (green curves) coil, position is the displacement of the Halbach array with respect to the corresponding coil pair corresponding to Fig. 4

Because no iron material is used in the actuator system no nonlinear effects like hysteresis or saturation occur. Hence the generated forces and torques depend linear on the coil currents and superposition can be assumed. Figure 5 shows the almost sin/cos- like proportionality factors calculated by FEM. Depending on the slider platform position this generated forces and torques can be transferred into the global Cartesian coordinate system. Thus the position depending relation $K(x,y)$ between the 6 coil currents $i_1 \dots i_6$ and the forces F_x , F_y , F_z as well as the torques M_x , M_y , M_z can be determined.

$$\begin{pmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{pmatrix} = K(x,y) \cdot \begin{pmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ i_5 \\ i_6 \end{pmatrix} \quad (1)$$

The (6x6)-Matrix $K(x,y)$ is invertible in the whole travel range and thus forms the basis for the commutation of the coils. With the inverse Matrix $K(x,y)^{-1}$ the force set points, calculated by a controller, can be converted into the set points for coil currents.

These simulation based results were checked by measuring of the magnetic flux density below the Halbach arrays. The horizontal flux component, which generates vertical forces, is shown in Fig. 6 and Fig. 7. The measured flux densities match well with the simulation results. Close to the Halbach array the horizontal component of the magnetic field shows harmonics of 5th and 9th order. But the coil geometry that is exposed to the magnetic field works like a filter function. Finally the forces are almost sinusoidal as shown in Fig. 5.

The final test for simulation accuracy was done by measuring the required coil currents in closed loop mode when the slider levitates at a fixed position. The maximum deviation from the predicted coil currents was less than 2.5 percent. This can be explained by simulation errors, variations of the magnetic properties and unexpected variations of the geometry or mounting of the Halbach arrays. The blue curves in Fig. 11 show the positioning behavior, caused by these deviations when moving with constant velocity. A system specific correction of the matrix $K(x,y)^{-1}$ can be derived from the deviation between predicted and measured coil currents when applying known loads to the system. Because of the linearity of the system the difference between measured and calculated coil currents is proportional to the known load and the error in the corresponding column of $K^{-1}(x,y)$. This allows, to determine a correction of the columns of $K^{-1}(x,y)$ which minimizes the position errors. The red curves in Fig. 11 show the result.

Fig. 6 Measured horizontal flux component over 4 magnetic periods along the roll axis of the Halbach array and chart over 1 magnetic period: harmonic distortions of 5th and 9th order 1 mm below the Halbach array

Fig. 7 Measured horizontal flux component over 4 magnetic periods along the roll axis of the Halbach array and chart over 1 magnetic period: small distortions in 4 mm distance

3. Thermal Management

Applying forces and torques generated by the slider platform weight to equation (1) the power losses caused by gravitation can be calculated from the necessary coil currents. In Fig. 8 the result for the first prototype can be seen. For a second prototype with a lighter slider platform and with stronger NdFeB-magnets Fig. 9 shows, that the power losses can be considerably reduced to less than 100 W. Because temperature stability is an important issue for highly accurate positioning technology the coils are equipped with very flat cooling sandwiches based on efficient liquid pipe technology. Thereby the temperature rise on the top of the coil housing remains less than 1.5 K for the first prototype and less than 0.3 K for the second prototype.

Fig. 8 Sum of power losses in all coils to carry the load of 5.3 kg with arrays of SmCo-magnets versus the slider position

Fig. 9 Sum of power losses in all coils to carry the load of 4.2 kg with arrays of NdFeB-magnets versus the slider position

4. Digital Controller

The control for all DOF of the platform is based on PI's digital industrial modular controller concept. The position controller uses six independent servo loops (Fig. 10). The position inputs of the servo loops are calculated by a coordinate transformation which transforms the measured sensor values to the DOF-positions. The current set points for the six amplifiers are calculated from the output of the servo loops, using the position dependent commutation matrix $K(x,y)^{-1}$. These set points are input of six PWM current amplifiers.

The real time operating system of the CPU is synchronized by a FPGA interrupt mechanism. The controller runs with a PC-ETX processing module with a servo cycle time of 200 μ s. Trajectory generation, simple to use command set and PI's real time interface is implemented. The necessary initialization and shutdown procedures are developed to drive the system in a well-defined starting position or switch it off at the parking position. An algorithm, which measures the necessary data and calculates the correction for the commutating matrix $K(x,y)^{-1}$ is developed. Hence the correction can be adjusted specifically to every system.

Fig. 10 Structure of the 6-axis controller of the PIMag6D

5. Results

The prototypes show position stability in the resolution of the sensor system. Also for fast dynamic motion sequences tracking errors are in the nm range when using correction matrices to compensate the difference between the FEM based commutation matrix $K(x,y)^{-1}$ and the true relation between forces/torques and coil currents. For the first prototype with analog amplifiers and SmCo-magnets the vertical force F_z was not included in this compensation. Fig. 11 shows the effect for a horizontal movement with 50 mm/s and 2 m/s². The difference between the blue and the red curves shows the strong influence of the correction matrices. For the second prototype with stronger NdFeB-magnets and PWM-amplifiers also a new compensation algorithm was developed which corrects the vertical force F_z too. Fig. 12 shows the result for the same type of motion. The differences with respect to Fig. 11 can be explained by the different environmental conditions like place of installation, the level of mechanical disturbances there and electrical disturbances, caused by the PWM-amplifiers. Nevertheless Fig. 12 shows that the new compensation algorithm works well for all degrees of freedom and improves the performance of the system considerably.

The controller setup in the prototype limits the maximum velocity to 100 mm/s at the moment but there are no physical limits caused by the structure. The high eigenfrequency of the platform assembly of more than 500 Hz allows high control bandwidth. The small noise level of all axes shown in Fig. 13 opens the way for further improvements with new high resolution sensor systems in the servo loops. In Fig. 14 circular motions of 2 different diameters can be seen. There are no hysteresis effects observed. The accuracy is in the nanometer level. Due to the z-travel of 100 μ m also Helix movements can be performed with some nm-resolution (Fig. 15).

Fig. 11 Horizontal movement with 50 mm/s without (blue curves) and with correction matrices (red curves) with the first prototype

Fig. 12 Horizontal movement with 50 mm/s without (blue curves) and with correction matrices (red curves) with the second prototype

Fig. 13 Position stability at position $x = y = 0$, $z = 50 \mu\text{m}$; $r_x = r_y = r_z = 0$; data for z , r_x and r_y are low pass filtered with band width of 400 Hz

Fig. 14 Circular motion in x-y-plane with diameters of $d = 10 \mu\text{m}$ and $d = 1 \mu\text{m}$, blue curve: measured positions, red curve: low passed positions ($f_{\text{Pass}} = 50 \text{ Hz}$, $f_{\text{Stop}} = 100 \text{ Hz}$, Stopband: -40 dB)

Fig. 15 Helix movements with a diameter of $10 \mu\text{m}$ and a z-velocity of $10 \mu\text{m/s}$ and $1 \mu\text{m/s}$

To evaluate the motion performance of the platform in vertical direction a measurement setup with a ZMI 4000 laser interferometer from Zygo with a resolution of 0.15 nm and a planar mirror on top the Mag6D platform according to Fig. 16 was used. The motion was controlled via the internal measurement and control system and observed with the laser interferometer. The Figure in the middle shows steps of 20 nm and the right Figure a zoom into the measurement data. Compared with Fig. 13 (upper right sub image) the standard deviation of the platform has improved from 6 nm to approximately 1 nm with the new compensation strategy (including the correction also for the vertical force F_z) and better environmental conditions in this setup.

Fig. 16 Measurement setup to evaluate the vertical motion performance and plots of 20 nm steps

6. Conclusion

A prototype of a 6 DOF planar magnetic levitation system with nanometer positioning capability as shown in Fig. 3 has been constructed. It comprises an integrated compact 6D sensor and is controlled by PI's modular E-712 digital nanopositioning controller, using precalculated commutation functions for the three coil pairs realizing a smooth path control. The PIMag6D platform can be scaled to various loads and travel ranges to meet the requirements of a variety of technologies like semiconductor processing, microscopy, life science and nanotechnology. Additional issues concerning the PIMag 6D system are described in (Gloess, et al., 2012), (Rudolf, et al., 2012) and (Schaeffel, et al., 2012 and 2014).

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References

- Gloess, R., Mock, C., Rudolf, C., Walenda, C., Schaeffel, C., Katzschmann, M. and Mohr, H.-U., Magnetic Levitation in 6DOF with Halbach Array Configuration, Proc. of Actuator 2012, International Conference, Bremen, June 2012
- Jansen, J.W., van Lierop, C.M.M., Lomonova, E.A., Vandenput, A.J.A., (2008), Magnetically Levitated Planar Actuator With Moving Magnets. IEEE Transactions on Industry Applications, Vol. 44, No. 4, July/August 2008
- Jansen, J.W., Janssen, J.L.G., Rovers, J.M.M., Paulides, J.J.H. & Lomonova, E.A. (2009). (Semi-) analytical models for the design of high-precision permanent magnet actuators. International Compumag Society Newsletter, 16(2), 4-17
- Kim, Won-jong and Trumper, D., High- precision magnetic levitation stage for photolithography, Precision Engineering 22:66-77 1998
- Kremers, M.F.J., Paulides, J.J.H., Janssen, J.L.G. & Lomonova, E.A. (2013). Design considerations for coreless linear actuators. IEEE Transactions on Magnetics, 49(5), 2271-2274.
- Ruben, S. D., Tsao, T.-C., Lemmons, T., Caskey, G. and Hocken, R., Intrinsic Damping of Linear Halbach Brushless Motors, Proc. of ASPE 2011, International Conference, Denver, November 2011
- Rudolf, C., Mock, C., Walenda, C., Gloess, R., Liang, R., Schaeffel, C., Katzschmann, M. and Mohr, H.-U., 6D Magnetic Levitation Positioning System with Compact Integrated 6D Sensor, Proc. of 12th euspen International Conference, Stockholm, June 2012
- Schaeffel, C., Katzschmann, M., Mohr, H.-U., Gloess, R., Rudolf, C., Mock, C. and Walenda, C., Planar Magnetic 6D Levitating System with compact Sensor, Proc. of ASPE 2012, International Conference, San Diego, October 2012
- Schaeffel, C., Katzschmann, M., Mohr, H.-U., Gloess, R., Rudolf, C., Mock, C. and Walenda, C., 6D Planar Magnetic Levitation System - Mag6D, ISMB14 – The International Symposium on Magnetic Bearings, Linz, August 2014