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Design and Control of a Six Degrees-of-Freedom Magnetically Levitated Positioning System

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Abstract: Magnetic levitation technology is a promising solution to achieve ultraprecision motion in vacuum environment as it is with the characteristics, e.g., non-contact, frictionless, and unlimited stroke. This paper presents the design and control of a six Degrees-Of-Freedom (DOF) magnetically levitated (maglev) positioning system. The maglev positioner is implemented by using four groups of Halbach permanent magnet arrays and coil stators. Through energizing the three-phase current in four coil arrays, the six DOF Lorentz force will be generated in the translator of the maglev system to conduct positioning. To control the maglev positioning system, the controllers of X and Y-axes are designed and optimized according to the specifications characterizing on the closed-loop performance of the maglev system, where the specifications are formulated as the linear matrix inequalities (LMIs) in the constrains of the created optimization. Finally, the experiments are conducted on the maglev prototype to demonstrate its positioning performance of the maglev positioning system.

Keywords: Magnetic levitation, positioning, Halbach PM array, motion control, low-order controller, linear matrix inequality.

1. INTRODUCTION

In recent years, Extreme Ultra-Violet (EUV) lithography process has emerged as the main solution to achieve shorter wavelength of the light to fabricate the smallest possible features on the wafer chips through photo lithographical exposure. As a result, high-resolution wafer fabrication lithography systems are currently developed with an EUV light source. Within these systems, the silicon wafers need to be exposed in high vacuum environment to prevent contamination of optical elements and absorption of the EUV light by air. Hence, magnetic levitation (maglev) has become the promising solution to provide frictionless support to the moving stages in such vacuum environment without risking contamination through air, and mechanical wear, from the air-bearings, and mechanical ball-bearing guides respectively.

The maglev positioning systems were first proposed in Trumper et al. (1996); Kim et al. (1998); Hocken et al. (2001) to conduct 6 DOF motion with relatively large-stroke xy planar movement. The one-directional (1D) Halbach Permanent Magnet (PM) array was adopted in such maglev positioning systems, as it can provide bi-directional magnetic field concurrently to provide both levitation and propulsion force in a 2 Degree-Of-Freedom (DOF) Moving Magnet Linear Motor (MMLM). Subsequently, the multi-DOF motions were realized by using the combination of several MMLMs with different orientations and coil configurations in Fespermana et al. (2012); Lu et al. (2012); Zhu et al. (2014); Teo et al. (2014) using same working principles, since this kind of maglev positioning systems has the advantages of low system complexities in regards of the current commutation, force allocation, and fabrication. Recently, planar Halbach PM arrays with two-directional magnet arrangement were also employed in the maglev positioning systems, e.g., Boeij et al. (2006); Jansen et al. (2007); Ueda et al. (2008); Nguyen et al. (2012), so that only one forcer in the moving translator can provide necessary force and torque for the multi-DOF motions. Since the 2D Halbach PM array suffers from the demerit of force ripple caused by the harmonic magnetic field, and many research are conducted to explore better 2D Halbach PM array in Cho et al. (2001); Min et al. (2010); Peng et al. (2013) with lower higher-order harmonics to reduce the force ripple.

In this paper, a maglev positioning system is presented to conduct 6 DOF motion. The implemented maglev system employs four MMLMs as the four forcers to provide force and torque, through energizing the three-phase current in four coil arrays, the required Lorentz force will be generated in the translator of the maglev system to conduct 6 DOF positioning. With the real-time position measurement provided by the capacitive sensors and laser interferometers, the proposed maglev positioning system is able to achieve a large-stroke planar motion up to

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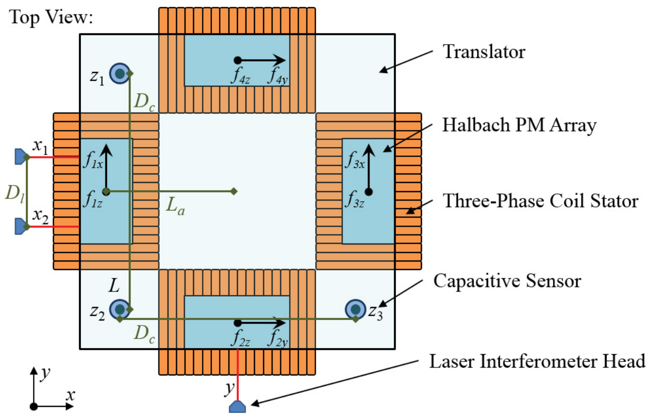

Fig. 1. The schematics of the maglev positioning system.

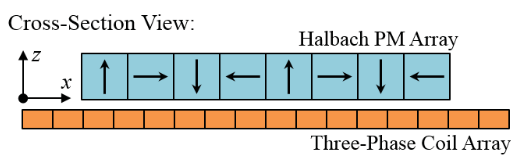

Fig. 2. The work principle of the 2-DOF Halbach moving magnet linear motor.

50 mm × 50 mm and the levitation height is up to 4 mm. A low-order controller is designed for the planar motion of the maglev positioning system, where the desired control specifications are formulated as the Linear Matrix Inequalities (LMIs) and the controller parameters are solved through the created optimization. Finally, the experiment is conducted on the maglev prototype to demonstrate its positioning performance.

2. MAGLEV SYSTEM AND MODELING

In this section, the design of the maglev positioning system is presented with the modeling.

2.1 Principle and Design of Maglev Positioning System

The schematics of the implemented maglev positioning system is illustrated in Fig. 1. The actuation of the maglev system is driven by four sets of 2 DOF MMLMs, which are utilized to provide the force and torque for the 6 DOF motion of the translator. Fig. 2 illustrates the work principle of the MMLM, where the MMLM contains a stator and a moving part. The moving part of MMLM is a Halbach PM array delivering sinusoidal magnetic field in both $x-$ and $z-$axes. The stator is formed by a three-phase coil array lying under the Halbach PM array. Through energizing the suitable current in the three-phase coil arrays in each set of MMLM, both levitation force f_{iz} (i=1, 2, 3, and 4) and propulsion force f_{ix} (i=1 and 3) and f_{iy} (i=2 and 4) are generated on the translator simultaneously. The 6 DOF motion of translator is actuated by the combined force of four MMLMs with the resulted torque. To obtain the real-time position of the translator, three channels of laser interferometers (x_1, x_2, and y) are used to measure the horizontal displacement, and three channels of capacitive sensors (z_1, z_2, and z_3) to measure the vertical displacement.

Fig. 3 shows the proposed design of the maglev positioning system. The four three-phase coil arrays are mounted on the

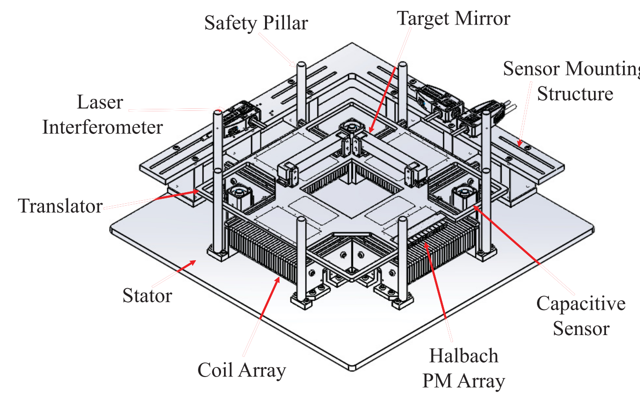

Fig. 3. Proposed design of maglev positioning system.

stator base with an overall dimension of 70 cm × 70 cm × 1.2 cm. Each coil array contains 30 rectangle coils, the length of coil, l_c, is 130 mm, the width of coil, w_c, is 6.67 mm, the height of coil, h_c, is 4 mm, and the turn number of coil, N_t, is 88. The input and output wires of all rectangle coils are connected to the terminal blocks and then configured into three-phase pattern. After assembling and wiring, each phase of the three-phase coil array has a resistance of around 32 Ω. In order to avoid the undesired electromagnetic effect and also provide certain damping for the motion, the aluminum is utilized to fabricate both the supporters and cores of the coil arrays, which also help to dissipate the heat generated in the coil arrays. The translator of the maglev positioning system is realized by a specific designed structure as shown in Fig. 3, where the four Halbach PM arrays are mounted on. Each Halbach PM arrays contains 12 PMs, and each PM is of the square cross-section with a width of 10 mm, and its length is 60 mm, and the magnetization magnitude of each PM is 1.3 T.

Two sets of Renishaw fibre optic laser interferometers are utilized, which afford three heads for both X and Y-axes displacement measurement. A L-shape sensor mounting structure is designed and fixed on the base of stator, and the three laser interferometer heads are installed on the L-shape structure to ensure that each two heads are parallel or perpendicular. The distance between x_1 and x_2, D_l, is designed as 76 mm, as illustrated in Fig. 1(a). Two low thermal expansion planar mirrors are utilized as the targets of laser interferometer, and both of them are mounted on the translator structure though the mirror mounting kits. Similarly, the squareness between the two mirrors are ensured by a designed L-shape structure during the installation. A set of Lion Precision CPL290 capacitive sensor system is employed to provide three-channel measurement of z-axis displacement. Three probe holders are designed to install the capacitive sensor probes, which also prevent the probes from accidental collision in the operating of maglev system.

2.2 Modeling of Maglev Positioning System

The control structure of the maglev positioning system is illustrated in Fig. 4. First, the 6-channel controller will compute the required force vector $\boldsymbol{F}$ based on the reference $\boldsymbol{r}$ and real position $\boldsymbol{\psi}$, which is acquired by the transformation of the raw sensor measurements $\boldsymbol{\chi}$. Next, the total force vector $\boldsymbol{F}$ will be allocated to each MMLMs, denoted as $\boldsymbol{f}$. Finally, the required