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Design and Simulation of a Testing Fixture for Planar Magnetic Levitation System Control Using Switched Reluctance Actuator

Norbert C. Cheung[1] Zhen Gang SUN[1] Shi Wei ZHAO[1] Wai-Chuen GAN[2]

[1]Department of Electrical Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong.
[2]R&D Motion, ASM Assembly Automation Ltd., Kwai Chung, N.T., Hong Kong
E-mail: norbert.cheung@polyu.edu.hk

Abstract - **Magnetic levitation systems are contactless type, there are no mechanical components between the translator and the stator. Hence, it can eliminate the mechanical wear, friction, noise, heat generation, and metal dust, satisfy environmental demand, and enable the system to move at high speed. Although the magnetic levitation systems have vast potential in engineering applications because of the above merits, the open loop instability and nonlinearity characteristics of the systems hamper its implementation. Therefore, the robust control is very important for the magnetic levitation systems. In this paper, the investigation, design, simulation and fabrication of a testing fixture for planar magnetic levitation system control are addressed, based on Switched Reluctance (SR).**

The proposed fixture uses three coils made by laminated silicon steel for levitation. This system has a much simpler structure, and it can lower manufacturing cost. In this paper, we firstly discussed the mechanical structure of the proposed planar magnetic levitation system. Secondly, Magnetic Circuit Analysis (MCA) was carried out to calculate the electromagnetic force. Then, the simulation of one single coil control is applied. The simulation results were very satisfactory and it validated the design concept. Finally, the control algorithm of the planar magnetic levitation system, which is a Multiple Input and Multiple Output (MIMO) system, was discussed.

Keywords – **Planar magnetic levitation system, switched reluctance actuator, design and simulation, magnetic circuit analysis**

I. INTRODUCTION

Study on magnetic levitation systems has been actively performed by worldwide researches due to the following reasons: (i)Conventional manufacturing processes e.g., belt-type conveyors or articulated robots generate dusts and pollution because of the mechanical friction or lubrication, and are inadequate to satisfy the environmental demands for precision products. (ii)Magnetic levitation system has the advantages of being contact-free, can eliminate the mechanical components, reduce the mechanical alignment and satisfies the environmental demands. (iii)Magnetic levitation vehicles are suitable for high speed operation, and the specific energy efficiency of magnetic levitation systems much exceeds that of both the turbo-jet aircraft and turbo-fan aircraft [1]. (iv)Magnetic levitation system is open loop instable and nonlinear in nature. This is a big challenge to make magnetic levitation an acceptable alternative to existing modes and implement widely.

There are four methods with the vast potential for the applicability of the magnetic levitation system [2]: (i) Permanent magnets method, (ii) Superconducting method, (iii) Eddy current method, and (iv) DC electromagnets method. And the common types of actuators for magnetic levitation systems are the short rotor Linear Induction Motor (LIM) with lateral stabilization [3], the magnetic levitated scheme uses Active Magnetic Bearings (AMB) [4], and the PM linear track with High-Temperature Super-Conductor (HTSC) support [5]. Those actuators produce sophisticated magnetic levitation systems that are efficient, but expensive to manufacture. Furthermore, the employment of rare-earth permanent magnet and high temperature superconductor produces additional manufacturing and maintenance problems to the system.

Comparing with the above actuators, Switched Reluctance (SR) actuator has a simple structure, and is cheap to manufacture. Hence, a proposed planar magnetic levitation system using SR actuator is initiated in this paper, by using SR drive technology, the actuator has a simple and robust structure with direct drive capability, and manufacturing of the actuator is easy, the magnetic circuit core can be made from laminated silicon steel plates, with the wires coil around the stator. Unlike other type of magnetic levitation systems, there are no expensive and hard-to-handle materials such as permanent magnet and superconductor. The proposed fixture is a Multiple Input and Multiple Output (MIMO) system, and it can be electromagnetic levitated. Hence, it can be used as a testing fixture to study the control algorithms for the MIMO planar magnetic levitation system.

The organization of this paper is as follows. The design of the planar magnetic levitation system using SR actuator and its modeling were discussed in Section II. In Section III, the Magnetic Circuit Analysis (MCA) method was employed to obtain the electromagnetic force. In Section IV, a single coil of the planar magnetic levitation system, which can be seen as a Single Input and Single Output (SISO) system, was simulated to achieve a stable and precision position control. The outline mathematical modeling of the planar levitation system was discussed in Section V. Finally, Concluding remarks are given in Section VI.

II. THE PLANAR MAGNETIC LEVITATION SYSTEM WITH SWITCHED RELUCTANCE ACTUATOR

Fig. 1 shows the schematic diagram of the MIMO planar magnetic levitation system with SR actuator, which is driven by three levitation coils, one on each center side of the equilateral triangular platform. The stators and translators are both made from laminated silicon steel plates. Three E type cores with coil windings are the stators, and three I type cores without coil windings are the translators. The stators are installed in the top plane, the translators are fixed in a plane below the stators, and each pair of stator and translator is aligned in vertical direction. When the stators are excited, in a magnetic circuit, the translators prefer to come to the minimum reluctance position at the instance of excitation. Hence, there will be electromagnetic force between the stator and translator. If the electromagnetic force is large enough, the plane with translators will be probably levitated. Three Linear Variable Differential Transformator (LVDT) position sensors are installed in each corner of the equilateral triangular top plane, and they are used to observe the vertical motion profile of the equilateral triangular levitation plane and provide the feedback positions.

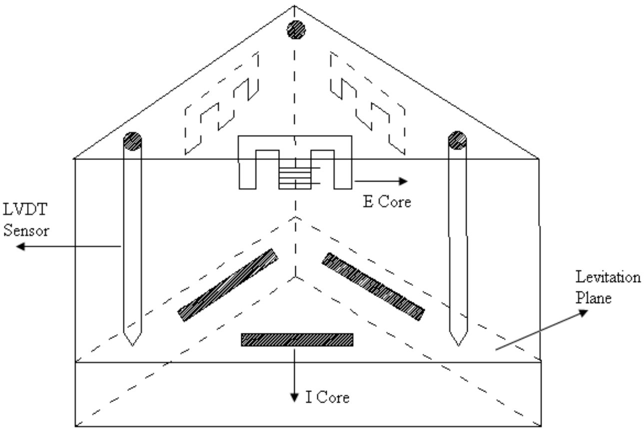

Fig. 1. Schematic diagram of the MIMO planar magnetic levitation system

III. THE MAGNETIC CIRCUIT ANALYSIS OF THE PLANAR MAGNETIC LEVITATION SYSTEM

Owing to its inherent complex flux characteristics, the SR actuator has not been widely used in magnetic levitation system. SRM derives its force from the change of flux; and flux exhibits a complex and nonlinear behavior. Therefore, the design of a magnetic levitation system with SR actuator is difficult. Hence, it is required to analyze the levitation force so as to validate the design methodology of the planar magnetic levitation system. Generally, there are two techniques which can be used to analyze electromagnetic force in the design of SR actuators. The two methods are referred as Magnetic Circuit Analysis (MCA) and Finite Element Analysis (FEA). Although FEA is quite accurate in calculation by spatial discretization, it is computational intensive and very time consuming. By contrary, MCA is simple and high efficient in computation, and its accuracy mostly depends on the choice of magnetic flux paths.

In this paper, the MCA method is adopted to calculate the electromagnetic levitation force. The schematic of one single levitation coil is shown in Fig.2. The three levitation coils are with same dimensions, therefore, the analysis of one coil is sufficient for the analysis of the actuator. The parameters of the single levitation coil are listed in Table 1.

Fig.3 shows the magnetic equivalent circuit diagram of the single levitation coil. Due to the high permeability of silicon steel, if the air gap is large and the core won't be saturation, the reluctance of cores can be ignored, hence only the reluctance of air gap is considered in the magnetic equivalent circuit.

TABLE I
PARAMETERS OF THE SINGLE LEVITATION COIL

Symbol	Definition	Value
W_{tp2}, W_{tp3}	Width of tooth 2 and 3 separately	16mm
W_{tp1}	Width of tooth 1	32mm
h	Tooth height	47mm
d	Tooth depth	20mm
W_{12}	Width between tooth 1 and 2	16mm
W_{13}	Width between tooth 1 and 3	16mm
l	Yoke height	16mm
D	Translator depth	20mm
H	Translator height	20mm
N	Number of coil turns	407

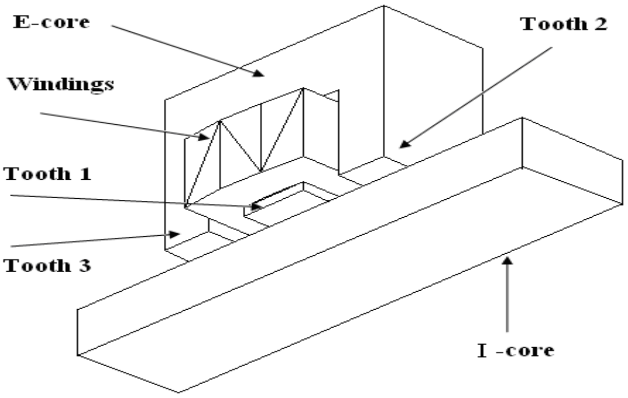

Fig. 2 Schematic of the single levitation coil model

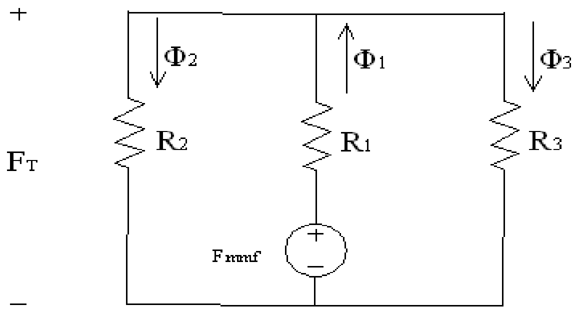

Fig. 3 Magnetic equivalent circuit diagram

3.1. Levitation force

The mmf equation can be written by using Ampere's circuital law:

$$F_{mmf} = \Phi_1 R_1 + \Phi_2 R_2 \tag{1}$$

$$\Phi_1 = \Phi_2 + \Phi_3 \tag{2}$$

$$F_T = \Phi_2 R_2 = \Phi_3 R_3 \tag{3}$$

$$R_2 = R_3 \tag{4}$$

Where Fmmf denotes the total mmf source, Φ denotes the flux, R denotes the reluctance and R=1/P, P is the air gap permeance. Substitution of (4) into (3) deduces:

$$\Phi_2 = \Phi_3 \tag{5}$$

The flux can be rewritten by substitute (5) and (2) into (1) as follows:

$$\Phi_1 = \frac{F_{mmf}}{R_1 + \frac{R_2}{2}} = \frac{F_{mmf}}{\frac{1}{P_1} + \frac{1}{2P_2}} \tag{6}$$

The mmf source of the coil is modeled by:

$$F_{mmf} = Ni \tag{7}$$

The inductance L corresponding to the coil is defined by:

$$L = \frac{N\Phi_1}{i} \tag{8}$$

The inductance can be calculated by the combination of (6), (7) and (8):

$$L = \frac{N^2}{\frac{1}{P_1} + \frac{1}{2P_2}} \tag{9}$$

The following simple but effective equation of levitation force can be employed [6]:

$$F = \frac{1}{2}\frac{\partial L}{\partial z} i^2 \tag{10}$$

Where F is the levitation force, z is the air gap distance, i is the winding current.

3.2. Air gap permeance

Once the air gap permeance are known, the levitation force can be calculated by implementing (9) and (10). The air gap permeance can be determined by selecting suitable flux paths. In this paper, the air gap permeance model used is based on [7] - [8]. The air gap has seven different types of flux paths to estimate air gap permeance, as shown in figure 4(a)-4(c). The derived air gap permeances are given in the following corresponding to each flux path:

Path 1 is the basic parallelepiped geometry,

$$P_{j1} = \mu_0 \frac{W_{tpj} d}{z} \tag{11}$$

Path 2 is quarter-circular cylinder geometry,

$$P_{j2} = \mu_0 \frac{\frac{1}{4}\pi z^2 d \Big/ 1.211z}{1.211z} = 0.535\mu_0 d \tag{12}$$

Path 3 is quarter annulus geometry,

$$P_{j3} = \int_z^{z+t} \mu_0 \frac{d}{\pi r/2} dr = 0.637\mu_0 d \ln\left(1 + \frac{t}{z}\right) \tag{13}$$

Path 4 is semicircular cylinder geometry,

$$P_{j4} = \mu_0 \frac{\frac{1}{2}\pi\left(\frac{z}{2}\right)^2 W_{tpj} \Big/ 1.211z}{1.211z} = 0.268\mu_0 W_{tpj} \tag{14}$$

Path 5 is half annulus geometry,

$$P_{j5} = \int_{z/2}^{t+z/2} \mu_0 \frac{W_{tpj}}{\pi r} dr = 0.318\mu_0 W_{tpj} \ln\left(1 + \frac{2t}{z}\right) \tag{15}$$

Path 6 is spherical quadrant geometry,

$$P_{j6} = \mu_0 \frac{\frac{1}{8}\times\frac{4}{3}\pi z^3 \Big/ 1.311z}{1.311z} = 0.304\mu_0 z \tag{16}$$

Path 7 is spherical shell quadrant geometry,

$$P_{j7} = \mu_0 \frac{1}{2}\frac{\pi/2\left(z + t/2\right)t}{\pi/2\left(z + t/2\right)} = 0.5\mu_0 t \tag{17}$$

Where j = 1 or 2, denotes the tooth 1 and tooth 2 respectively, μ_0 is the permeability of air, W_{tp} is the width of tooth, d is the tooth depth, h is the tooth height, $t = h/12$.

The inductances of each path can be obtained by solving the equations set of (6)-(8) and (11)-(17), and the total inductance $L(i,z)$ for the coil with all magnetic flux paths is calculated as:

$$L(i,z) = \sum_{k=1}^{7} L_k(i,z) \tag{18}$$

The levitation force can be calculated by the combination of (10) and (18). Fig.5 shows the force-current-position diagram by using the MCA model.

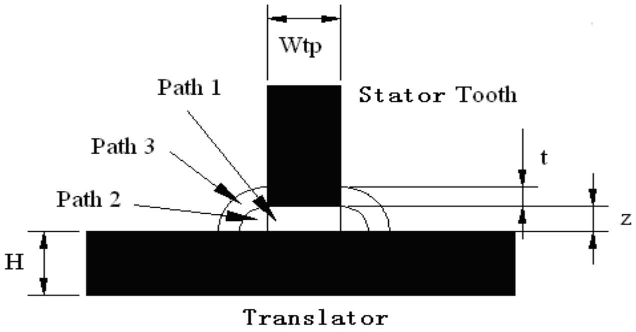

Fig. 4(a) Flux paths from front view

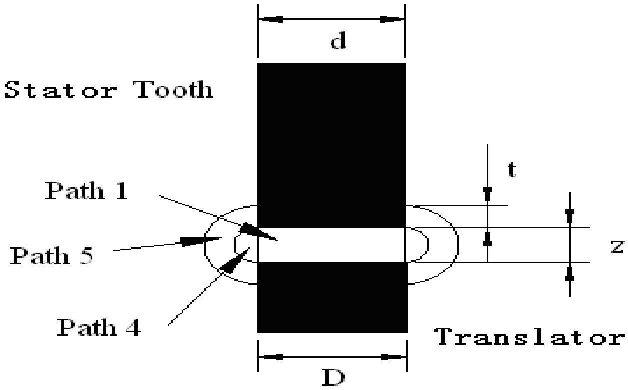

Fig. 4(b) Flux paths from side view

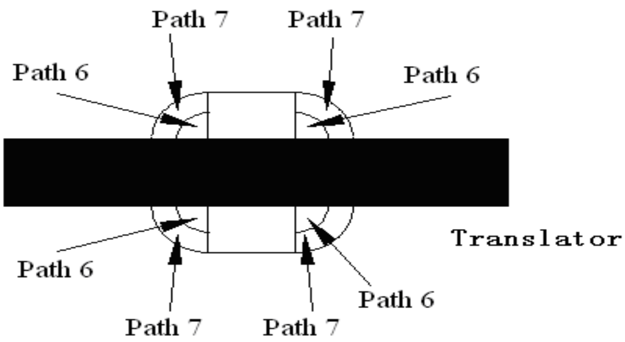

Fig. 4(c) Flux paths from top view

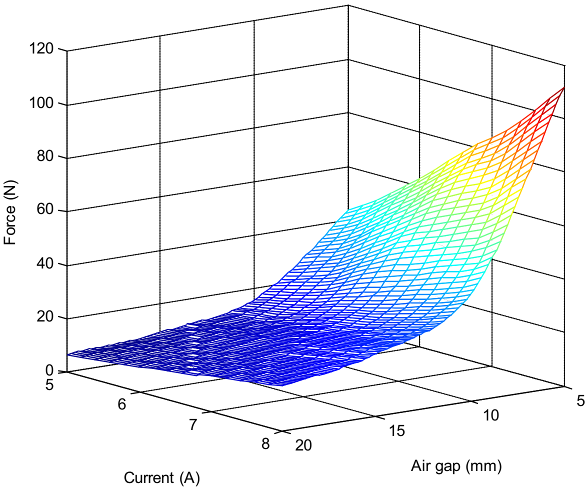

Fig. 5 The diagram of force-current-position by MCA model

It can be seen from fig.5 that the electromagnetic force is nonlinear, and the levitation force (I=7A, z=15mm) is about 17N. Hence, if the three coils act together, the levitation force will be 51N or so, which is enough to levitate the plane which is totally around 2kg.

IV. SIMULATION OF SISO SINGLE COIL LEVITATION

The magnetic levitation control composes of three levitation coils and is shown in fig.1. In order to study the magnetic levitation characteristics from step to step, the levitation of one single coil, which is a SISO system, will be investigated firstly. The proposed control algorithm is independent among these three coils. The primary control variable is a position set-point, the levitation gap, and the vertical disturbance force f_d is taken into account. Therefore, a feed forward force compensation term f_c can be applied to cancel the effect of the disturbance force. Fig.6 shows the control algorithm block diagram.

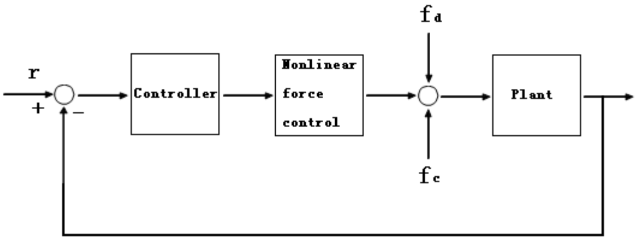

Fig. 6 The control block diagram for single coil

The nonlinear mathematical model of the levitation coil can be described by the following equations:

$$f_z = M\frac{d^2 z}{dt^2} + f_g + f_d \qquad (19)$$

Where f_z is the electromagnetic force generated by levitation coil, z is the air gap, f_g is the total gravity of the levitation plane.

For the nonlinear force control of the levitation coil, the current-force-position force calculated in Section III can be used in lookup table, and the equation (10) can be simplified as:

$$f_z = \frac{1}{2}N^2 A\mu_0 \frac{i^2}{z^2} \qquad (20)$$

Where N is the winding turns of levitation coil, A is the area of cross section of the air gap, μ_0 is the magnetic permeability of air, i is the current, and z is the air gap distance.

According to the above control algorithm, the single levitation coil control is simulated by using Matlab Simulink, to verify whether the coil can achieve a stable and precision position control. In this case, the classic PID control will be employed as the controller.

Fig.7 shows the schematic of displacement of single levitation coil. At the initial state, the air gap between the stator and the translator is 15mm. And we set the reference input air gap 8 mm at steady state.

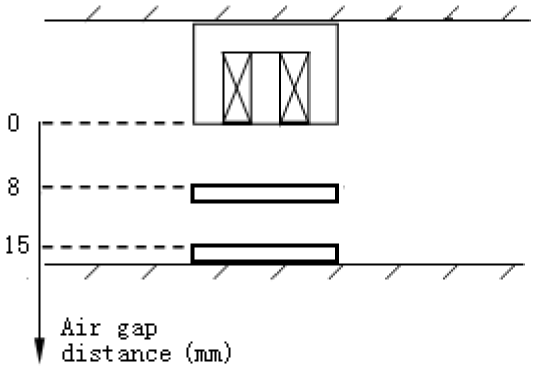

Fig. 7 Schematic of displacement of single levitation coil

Fig.8 is the simulation results of the single levitation coil according to above control algorithm, fig.8 shows the output position response curve.

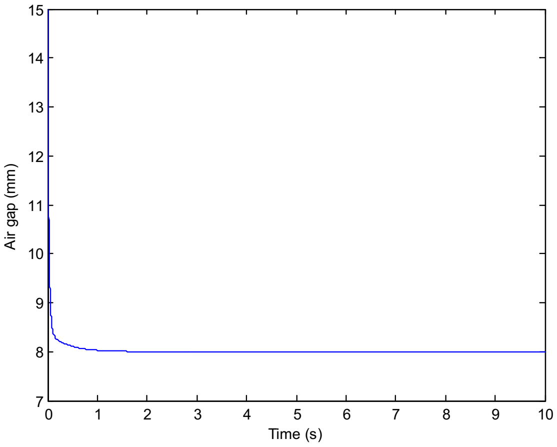

Fig. 8 The output position response curve

Fig. 8 shows that total force can balance and maintain the output position in a stable manner. The plane can be levitated in a stable and precision position state.

V. OUTLINE MATHEMATICAL MODELING OF THE PLANAR MAGNETIC LEVITATION SYSTEM

The MIMO planar magnetic levitation fixture is a multivariable control system, and it can be seen as a rigid body. In a Cartesian coordinates, the system has six degrees of freedom, three translational motions and three rotational motions, which is shown is fig.9. Although the system has six degrees of freedom, movement of the levitation plane can be restricted in particular directions. Owing to the unique magnetic circuit structure of the SR actuator, the stators and the translators will move automatic alignment. Hence, the translational movement along X axis and Y axis, and the yawing movement around Z axis can be reasonable ignored. The simplified motion equations about the mass center of the levitation plane are:

$$\begin{cases} F_z = M\ddot{z} \\ T_{roll} = I_{xx}\ddot{\phi} \\ T_{pitch} = I_{yy}\ddot{\theta} \end{cases} \qquad (21)$$

$$\begin{cases} F_z = f_1 + f_2 + f_3 \\ T_{roll} = (f_2 - f_3)a/4 \\ T_{pitch} = (f_2 + f - 2f_1)\sqrt{3}a/12 \end{cases} \tag{22}$$

$$\begin{cases} z = (z_1 + z_2 + z_3)/3 \\ \phi = (z_1 - z_3)/a \\ \theta = (2z_2 - z_1 - z_3)4\sqrt{3}/(3a) \end{cases} \tag{23}$$

Where M is the total mass of the levitation plane, I_{xx} and I_{yy} are moments of inertia, a is the side length of the equilateral triangle, ϕ and θ are the Euler angles.

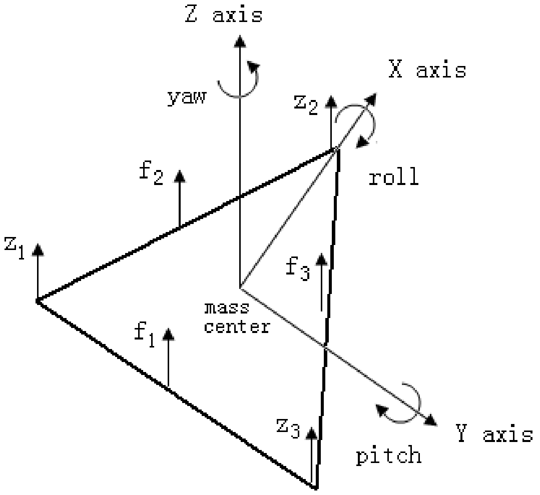

Fig. 9 Schematic of the motion model

The electromagnetic force equation and the voltage differential equation can be linearized by Taylor series expansion at the nominal operating point (i_0, z_0) when the error between variation and nominal point is very small, the levitation force produced by any jth magnet may be expressed as:

$$f_j(t) = -k_i i_j(t) + k_z z_j(t) + f_d(t) \tag{24}$$

$$\frac{di_j}{dt} = \frac{k_z}{k_i}\frac{dz_j(t)}{dt} - \frac{R}{L_0}i_j(t) + \frac{1}{L_0}v_j(t) \tag{25}$$

Where

$$k_i = \frac{\mu_0 N^2 A i_0}{2z_0^{\ 2}},\ k_z = \frac{\mu_0 N^2 A i_0^{\ 2}}{2z_0^{\ 3}},\ L_0 = \frac{\mu_0 N^2 A}{2z_0}$$

Fig.10 shows the simplified control algorithm block diagram.

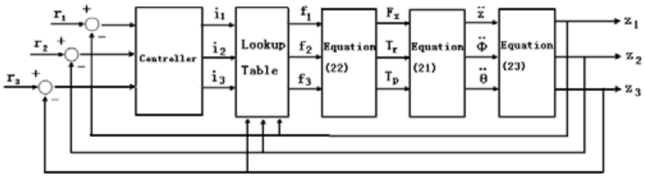

Fig. 10 The control block diagram

VI. CONCLUSIONS

A testing fixture for planar magnetic levitation system control using SR actuator is proposed in this paper. There are no PMs required in the proposed actuator so that the total cost can be lower. MCA method is performed to simulate the electromagnetic force, which can measure whether the levitation force could satisfy the design methodology.

The SISO single coil levitation system is simulated by Matlab Simulink according to the control algorithm; the simulation results show the levitation system can achieve a stable and precision position control.

The outline mathematical modeling of the MIMO planar magnetic levitation system is discussed. And the control algorithm for this MIMO system need to be further investigated.

Fig. 11 shows the experimental prototype of the planar magnetic levitation system with SR actuator. Actually, in future publication, experimental results will be analyzed and reported.

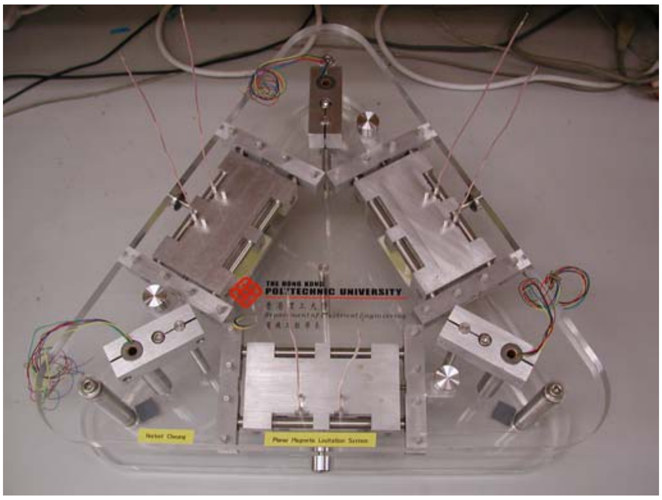

Fig. 11 The experimental prototype of the proposed system

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BIOGRAPHY

Norbert C. Cheung (S'85-M'91-SM'05) received his BSc, MSc, and PhD from the University of London, University of Hong Kong, and University of New South Wales in 1981, 1987, and 1995 respectively. His research interests are motion control, actuators design, and power electronic drives. He is now working in the Department of Electrical Engineering of the Hong Kong Polytechnic University.

Zhen Gang Sun (S'08) received both the BSc degree and MSc degree from South China University of Technology, Guangzhou, China, in 2000 and 2003, respectively. He is currently pursuing the PhD degree in the Department of Electrical Engineering, the Hong Kong Polytechnic University, Kowloon, Hong Kong. His main research interests are motion control and magnetic levitation machines.

Shi Wei Zhao (S'07-M'09) received the BSc degree from Central South University, Changsha, China, the MSc degree from South China University of Technology, Guangzhou, China, the PhD degree from The Hong Kong Polytechnic University, Hong Kong, in 2000, 2003 and 2008, respectively. He is currently pursuing the PhF degree in the Department of Electrical Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong. His main research interests are motion control and machine drives.

Wai-Chuen Gan (S'94-M'02-SM'06) received the BEng degree (with first-class honors and the academic achievement award) in electronic engineering and the MPhil and PhD degrees in electrical and electronic engineering from the Hong Kong University of Science and Technology, Hong Kong, China, in 1995, 1997 and 2001, respectively. From 1997 to 1999, he was a Motion Control Application Engineer at ASM Assembly Automaton Ltd, Hong Kong, China. He rejoined the same company in 2002, and is responsible for the development of linear switched reluctance motor systems for semiconductor assembly equipment. His current research interests include robust control of ac machines, power electronics, design and control of linear switched reluctance motors.