Design and Simulation of a Magnetic Levitated Switched Reluctance Linear Actuator System for High Precision Application

Zhengang Sun*, Norbert C. Cheung*, Jianfei Pan*, Shiwei Zhao*, and Wai-Chuen Gan**
*Department of Electrical Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong.
**R&D Motion, ASM Assembly Automation Ltd., Kwai Chung, N.T., Hong Kong
E-mail: norbert.cheung@polyu.edu.hk

Abstract - **Magnetic levitated carrier system was developed for the transportation systems. It is contact-free type; it can eliminate mechanical components (e.g. gears, guide, ball bearings), reduce the mechanical alignment and maintenance cost, satisfy environmental demand, and enable the carrier to travel at high speed with high precision and acceleration. In this paper, the investigation, design, simulation and fabrication of a magnetic levitated linear motion system are addressed, based on Switched Reluctance (SR). The proposed system resolves the problems of mechanical wear, friction, noise, heat generation, and "metal dust" contamination, and it is very suitable for applications that require high-performance linear motions: from high-precision manufacturing machines, clean-room wafer carrier systems, to high-speed material transportation in factories and warehouses.**

The proposed system employs a novel linear machine structure which uses four coils for levitation, and three coils for propulsion. Comparing to Permanent-Magnet (PM) track levitation, high-temperature superconductor levitation, and other existing magnetic levitation methods, the proposed system has a much simpler structure. It can lower manufacturing cost and increase reliability. In this paper, we firstly discussed the mechanical structure of the proposed levitation system and the model of the actuators. Then, Finite Element Analysis (FEA) was carried out for both the propulsion and levitation actuators to verify the electromagnetic characteristics of the motion system. Finally, a control algorithm, which includes PID and nonlinear force control was discussed. The levitation system was simulated by Matlab Simulink, to achieve a stable and high-precision position control. The simulation results were very satisfactory and it validated the design concept.

I. INTRODUCTION

In manufacturing processes, working environment affects the quality of the precision products. Conventional transportation systems e.g., belt-type conveyors or articulated robots generate dusts and pollution due to the mechanical friction or lubrication, and are inadequate to satisfy the environmental demands. Magnetic levitated carrier system for the transportation systems has the advantages of being contact-free , can eliminate the mechanical components e.g., gears, guide, ball bearings, reduce the mechanical alignment and maintenance cost, hence it satisfies the environmental demands. Therefore, research on contact-free type transportation system and actuator has been actively performed by worldwide researchers.

The most common form of motors for magnetically levitated carrier systems motor is the synchronous Long Stator Motor (LSM) with Lateral stabilization [1], the magnetic levitated scheme uses Active Magnetic Bearings (AMB) [2,3], and the Permanent-Magnet (PM) linear tracks with High-Temperature Super-Conductors (HTSC) support [4].

The above methodologies produce sophisticated magnetic levitation systems that are efficient, but expensive to manufacture. In addition, the employment of rare-earth permanent magnet and high temperature superconductor produces additional manufacturing and maintenance problems to the system.

On the other hand, Switched Reluctance Motor (SRM) has a simple structure and high levels of performance, it is cheap to manufacture. Due to concentrated, the motor can provide high efficiencies & high specific outputs comparable with the widely used ac motors [5].

Hence, the development of a novel, high-performance, magnetic-levitated, direct-drive linear motion system for high-precision and high-speed material transport application is initiated. The proposed motion system is targeted for industrial automation machines. Unlike passenger transportation system, the linear motion system is comparatively small in size, with a small carrier load. However, it must be simple in structure, easy to manufacture, and highly robust under large temperature range. Also, the linear motion system should not contain expensive components or hard to handle materials.

In this paper, a novel magnetic levitated linear actuator based on Switched Reluctance (SR) driving principle is proposed. By using SR drive technology, the linear actuator has a simple and robust structure with direct drive capability, and it is particularly suitable for high speed and high precision operation. Manufacturing of the actuator is simple, the magnetic circuit can be made from laminated mild steel plates, the moving part can be made from simple coil windings and metal pieces. Unlike other type of magnetic levitation systems, there are no expensive and hard-to-handle materials (e.g. permanent magnet, super conductor). The proposed can be operated under harsh environments with large temperature differences.

978-1-4244-1666-0/08/$25.00 ©2008 IEEE

The organization of this paper is as follows. The design of the magnetic levitated SR linear actuator and its modeling were discussed in Section II. In Section III, the Finite Element Analysis (FEA) was carried out for both the propulsion and levitation actuators to verify the electromagnetic characteristics of the motion system. In Section IV, a control algorithm including PID control and nonlinear force control was discussed and the levitation system was simulated to achieve a stable and high-precision position control to validate the design concept. Concluding remarks are given in Section V.

II. THE MAGNETIC LEVITATED SWITCHED RELUCTANCE LINEAR ACTUATOR

Fig. 1 shows the layout of the magnetic levitated SR linear actuator, which is driven by three propulsion coils and four separated levitation coils, one on each corner of the moving platform.

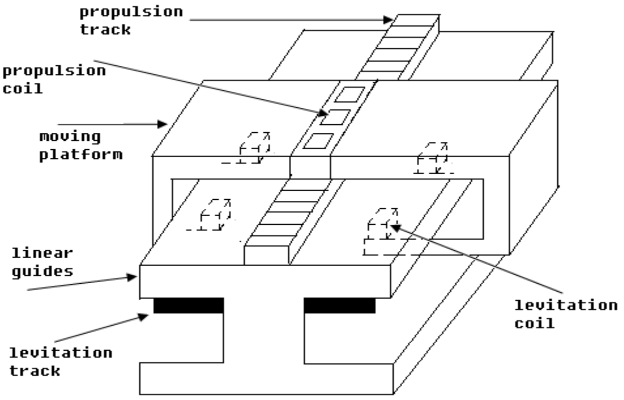

Fig. 1. Layout of the Magnetic Levitated SR Linear Actuator

An optical encoder with 1um resolution is installed in the propulsion axis to observe the horizontal motion profile and provide the feedback position. Four proximity analog position sensors are located on the four corners of the moving platform, to measure air gap between the moving platform and the track rails, and provide the feedback position. This ensures a constant air gap to achieve the stable and high-precision position control. The propulsion track has a tooth structure rail track, with three separate coils to provide the positive and negative horizontal forces. The levitation track, on the other hand, has a smooth profile, and it only provides the lifting forces to the moving platform. During acceleration or deceleration, irregular downward force will be created by the three propulsion coils. This additional force needs to be compensated by four levitation coils through appropriate control method.

Since the moving platform runs on a straight line, there is no need to install guidance coils to compensate for the lateral forces. Moreover, the unique magnetic circuit structure of the SR linear actuator makes the moving platform automatic self-centered, eliminating the need for any additional guidance mechanism.

The motion specifications of the proposed levitated system are listed in Table I.

TABLE I
Motion Design Specifications

Mass of the platform	3kg
Maximum loading	3kg
Maximum acceleration	$10m/s^2$
Maximum velocity	1m/s
Maximum force	60N
Peak power of the motor	60W
Position accuracy	10um

III. THE FINITE ELEMENT ANALYSIS (FEA) SIMULATIONS OF THE PROPOSED ACTUATOR

Fig. 2 shows the simplified 2D drawing of the proposed actuator. At the development stage, the air gap length is fixed at 1.25 mm.

3.1 Performance Prediction

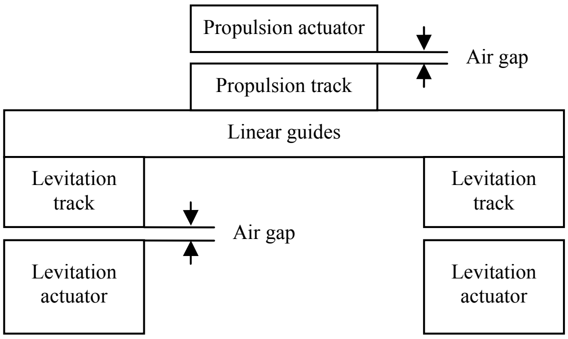

Fig. 2. Simplified 2D drawing of the proposed actuator

To further verify the electromagnetic characteristics of the motion system, a series of FEA and experiments have been carried out for both the propulsion and levitation actuator. The main goal of the design for the levitation actuator focused on the counteraction from the weight of the whole moving platform and vibrations of the moving platform. From Table I, we know the maximum weight of the whole moving platform is 60 N or so. And the normal forces of propulsion and levitation actuator are respectively analyzed by Finite Element Method.

3.2 Propulsion Performance

Fig. 3 shows the schematic of propulsion actuator model in the proposed system. To accompany the extreme case that the levitation system has the maximum air gap length, the propulsion system also reaches its minimum value, 0.5 mm. An analysis for the force output for both axis has been carried out for the propulsion system. Fig. 4 shows the results and comparisons of propulsion force by FEA & experiment. Fig. 5 shows results of normal force in propulsion axis by FEA.

3.3 Levitation Performance

The levitation actuator is assembled in U-shape as shown in Fig. 6 so as to ease the mass production. In order to fully characterize the proposed levitation system, three dimensional finite element models are directly built. The objective of finite element analysis is to evaluate the normal force value under different current levels and air gaps. Since four levitation coils are identical, the analysis of only one is sufficient for the analysis of the actuator. Fig. 6 shows the schematic of the single levitation coil model.

The simulation takes into account of the cases air gap change from 0.5 mm to 2 mm; this is to test whether the levitation actuator are capable of compensating for weight of the whole moving platform and the normal force generated by the propulsion actuator under real operations. The normal force of the levitation coil can be derived from FEA at different current excitation levels and air gaps as shown in Fig. 7.

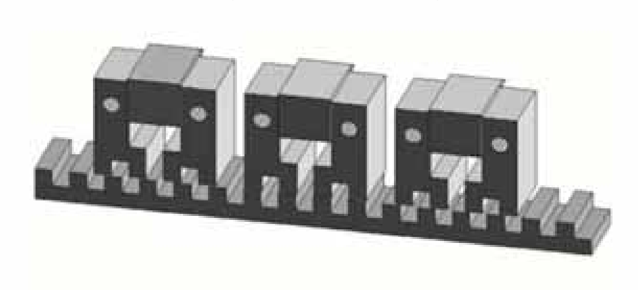

Fig. 3. Schematic of the propulsion actuator model

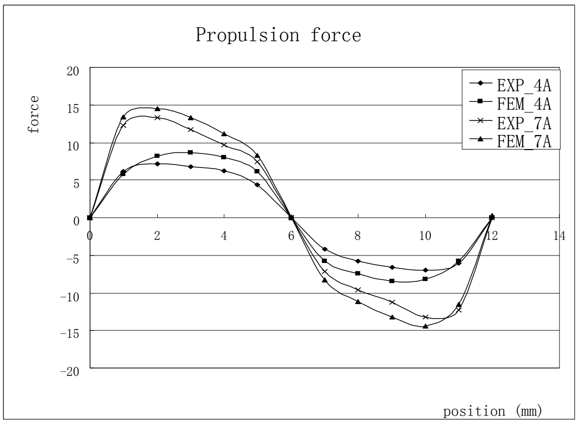

Fig. 4. Propulsion force of the propulsion actuator

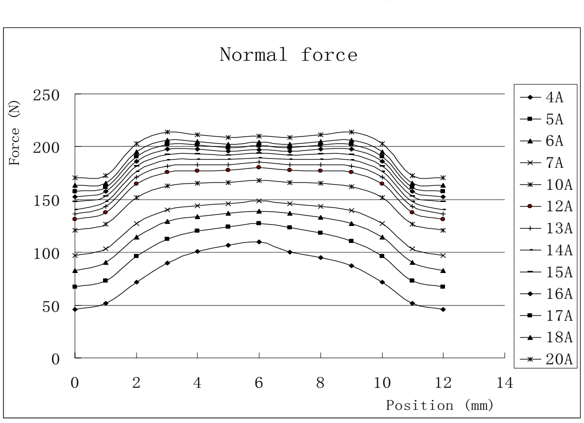

Fig. 5. Normal force of the propulsion actuator

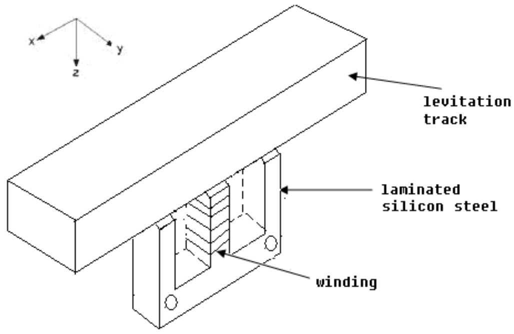

Fig. 6. Schematic of the single levitation coil model

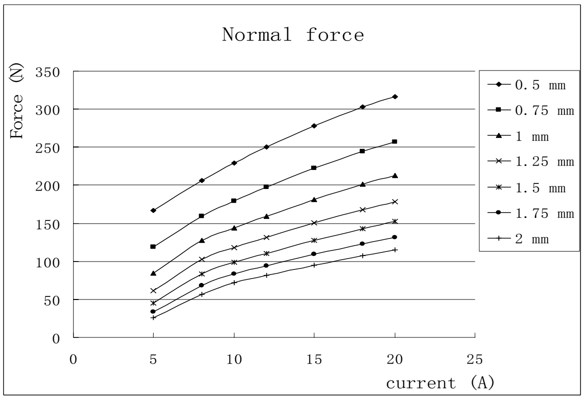

Fig. 7. Normal force of one levitation coil

3.4 Compensation Result

The worst case of compensation is that the propulsion air gap is 0.5 mm, as well as the levitation air gap is 2 mm, because at this moment the normal force of propulsion actuator is maximum and the normal force of levitation actuator is minimum. It can be concluded that the normal force of levitation actuator can compensate the weight of the whole moving platform and normal force of propulsion actuator by comparing the force of Fig. 5 & Fig. 7. For example, under the worst situation, when the propulsion coil current is 10 A, & 20A, the normal force of propulsion actuator is about 180 N & 210 N respectively; when the levitation coil current is 10A, the four levitation coils can produce a normal force 280 N altogether, which is enough to compensate the weight of the whole moving platform and normal force of the propulsion actuator.

IV. CONTROL ALGORITHM

The force and position control algorithm of the proposed levitated system can be divided into two parts. The first part is the magnetic suspension control (z-axis) and the second part is the propulsion control (x-axis). The detailed control algorithms are addressed in this section.

4.1 Propulsion axis control

As shown in Figure 1, the propulsion force in x-axis is generated by the SR linear actuator in propulsion axis. The mathematical model of the SR linear actuator for a single phase is given by [6],

The nonlinear mathematical model of the SR linear actuator in propulsion axis can be described by the following equations:

Actuator winding voltage balancing equations:

$$v_j(t) = R_j i_j(t) + \frac{\partial \lambda_j(i_j(t), x(t))}{\partial x(t)} \frac{dx(t)}{dt} + \frac{\partial \lambda_j(x(t), i_j(t))}{\partial i_j(t)} \frac{di_j(t)}{dt} \qquad (1)$$

Torque equations:

$$f_j(i_j(t), x(t)) = \frac{\partial \int_0^{i_j} \lambda_j(i_j(t), x(t)) di_j}{\partial x(t)} \qquad (2)$$

where $v_j(t)$, $i_j(t)$, R_j, $\lambda_j(i_j(t), x(t))$ are the phase voltage, phase current, phase resistance, and phase flux linkage respectively, x is the travel distance in propulsion axis, $f_j(i_j(t),x(t))$ is the generated electromechanical force for this phase.

The propulsion axis force and position control of LSRM had been developed extensively by the authors in [6, 7, 8, 9, 10, 11]. The sophisticated force linearization scheme and the robust position controller are employed in this levitated actuator so that the specified 10um position accuracy can be achieved. The detailed control algorithm design and implementation can be found in the above references and will not be addressed here.

4.2 Magnetic Levitation Control

The magnetic levitation control composes of four levitation coils and is shown in Fig. 1. The proposed control algorithm is independent among these four coils. The primary control variable is a position set-point, the levitation gap; however, there is always a z-axis force disturbance applied to the proposed control algorithm. Fig. 8 shows the proposed control algorithm block diagram.

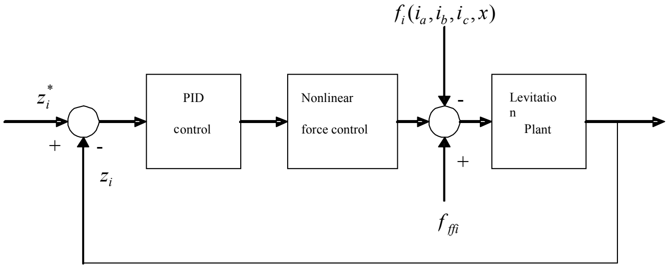

Fig. 8. The control block diagram for the levitation coil – single coil

In Fig. 8, z_i* is the levitation air gap, z_i is the feedback z-axis position information which is provided by a proximity analog position sensor. When the propulsion actuator is excited to generate propulsion force, z-axis normal attraction force is also created. Therefore, these four levitation coils are required to generate counter-force in order to levitate the whole moving platform. The z-axis attraction force can be estimated using FEA software, and Fig. 5 shows the simulation results of the z-axis attraction force for our proposed actuator.

Although the disturbance force f_i (i_a, i_b, i_c, x), a quarter of the total normal attraction force and the gravity of the moving platform, is highly nonlinear, we can still estimate it accurately by simulation. Therefore, a feedforward force compensation term, f_{ffi} in Fig. 8, can be applied to cancel the normal attraction force generated by the propulsion actuator. Finally, a consistent levitation gap can always be maintained.

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

$$f_z = M \frac{d^2 z}{dt^2} + f_g + f_i \qquad (3)$$

Where f_z is the normal force generated by levitation coil, z is the air gap, f_g is the gravity of moving platform, f_i is the normal attraction force of propulsion actuator.

For the nonlinear force control of the levitation coil, the following simple but effective current-force-position equation can be employed [12]:

$$f_z = \frac{1}{2} N^2 A \mu_0 \frac{i^2}{z^2} \qquad (4)$$

Where f_z is the normal force generated by levitation coil, 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 height of air gap. From equation 4, we know that the normal force of levitation coil is proportional to i^2 and inversely proportional to z^2.

4.3 Simulation Control Result of Single Levitation Coil

According to the first part control algorithm of the proposed levitation system above, we further simulate levitation control (z-axis) of single levitation coil by using Matlab Simulink V6.1, to verify whether the system can achieve a stable and high-precision position control.

Fig. 9 shows the schematic of displacement of single levitation coil. At the initial state, the air gap between the coil and the levitation track is 2mm. And we set the reference input air gap 1.25mm at steady state. Note that the levitation coil is not energized in the horizontal direction (x-axis), the displacement in x-axis in Fig. 9 is to show the situation when the platform of the actuator is moving.

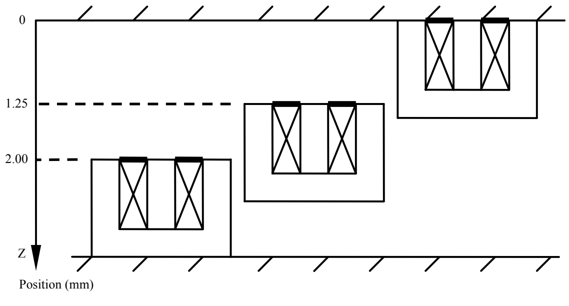

Fig. 9. Schematic of displacement of single levitation coil

The following factors are considered in simulation:

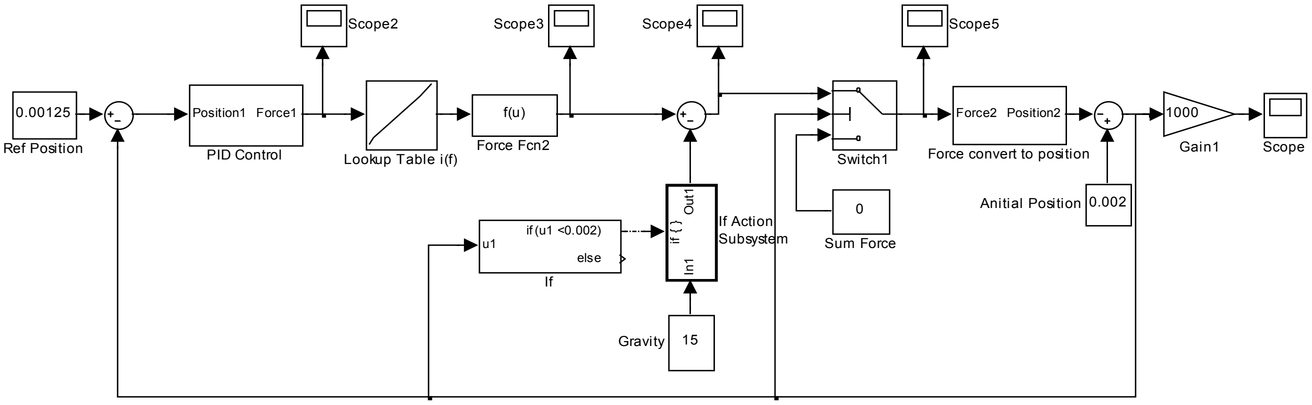

Fig. 10. The control block diagram for the levitation system

1. PID control method is used to control the levitation system;
2. The normal force of levitation coil is nonlinear, it can be performed by a current–force–position lookup table;
3. The range of air gap between the levitation coil and the levitation track is 0-2mm;
4. When the air gap is 2mm, the gravity of coil is counteracted by the support force, and the gravity of coil will act on the motion of coil once the air gap of coil is less than 2mm;
5. When the air gap is 0mm, the levitation track will stop coil move up. If the normal force of levitation force is over the gravity of the moving platform, the composition of total force is zero.

According to the magnetic levitation control algorithm and the factors above, we use Matlab Simulink to simulate the levitation system. Fig. 10 shows the proposed levitation system control block diagram, Fig. 11 shows the output position response curve, Fig. 12 shows the composition of force response curve.

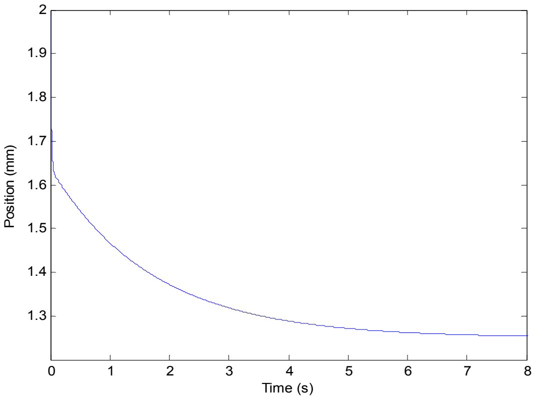

Fig. 11 The output position response curve

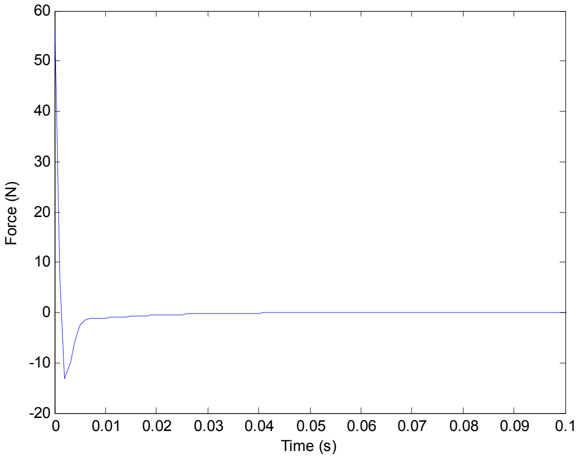

Fig. 12 The composition of force response curve

Fig. 11 & Fig. 12 show that the composition of force can balance and maintain the output position in a stable manner. The moving platform can be levitated in a stable and high-precision position state. However, the response time of the levitation process is about 7s.

In summary, with the proposed magnetic and propulsion axes control, the newly developed levitation system can run in a contact-free environment with the specifications given in Table I.

V. CONCLUSIONS

A new magnetic levitated switched reluctance linear actuator system is proposed in this paper. There are no PMs required in the proposed actuator so that the total cost can be lower. Furthermore, some special requirements of practical applications, such as high temperature working environment and PM free test station, can be fulfilled naturally using the newly developed actuator.

The magnetic levitated system is basically composed of a maturely developed LSRM by the authors and four magnetic levitation coils. Extensive FEA simulations are performed to ensure that both the force generation for the levitation and propulsion axes are feasible to satisfy the motion specifications listed in Table 1.

A simple but effective levitation and propulsion force and position control algorithm is introduced in section 4 so that the completed magnetic levitation system can be constructed.

The levitation system is simulated by Matlab Simulink V6.1 according to the control algorithm; the simulation results show the levitation system can achieve a stable and high-precision position control.

Fig. 13 shows the experimental installation of magnetic levitated SR linear actuator. Actually, in future publication, experimental results will be analysed and reported.

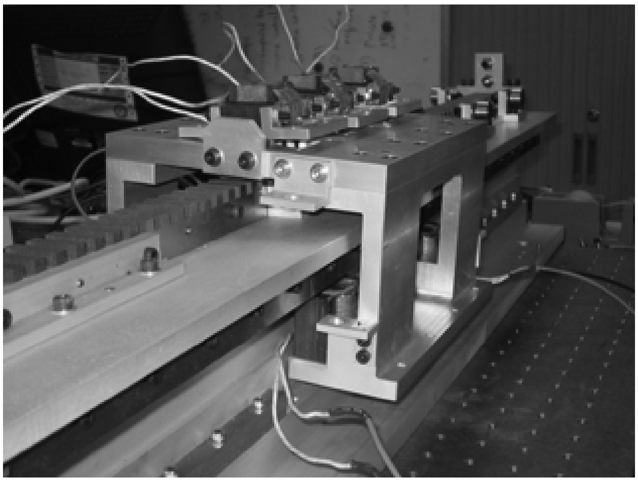

Fig. 13 The magnetic levitated SR linear actuator experimental installation

Accurate position control of SR magnetic levitated actuator is new to literature and the proposed system introduced in this paper provides a useful experience to the precision motion control industry.

ACKNOWLEDGMENT

The authors would like to thank the University Grants Council for the support of this project through the project codes: PolyU 5141/05E.

REFERENCES

[1] Venkataratnam, K. & Chattopadhyay, A. B, “Analysis of electromagnetic forces in a levitated short rotor LIM I & II,” IEEE Trans. on Energy Conversion 17(1):95-106, 2002.

[2] Hajjaji, A. & Ouladsine, M, “Modelling and nonlinear control of magnetic levitation systems,” IEEE Trans. on Industrial Electronics 48(4):831-838, 2001.

[3] Komori, K. & Yamane, T, “Magnetically levitated micro PM motors by two types of active magnetic bearings,” IEEE/ASME Trans. on Mechatronics 6(1):43-49, 2001.

[4] Nagashima, K. et. Al, “Controlled levitation of bulk superconductors,” IEEE Trans. on Applied Superconductivity 10(3):1642-1648, 2000.

[5] Lawrenson, P. J. et. al., “Variable-speed switched reluctance motors,” IEEE Proc., 127(4):253-265, 1980.

[6] Gan, W. C. et. al., “Position control of linear switched reluctance motors for high precision applications,” IEEE Trans. on Ind. Applications, 39(5):1350-1362, 2003.

[7] Gan, W. C. & Cheung N. C, “Development and control of a low-cost linear variable-reluctance motor for precision manufacturing automation,” IEEE Trans. on Mechatronics, 8(3):326-333, 2003.

[8] Gan, W. C. et. Al, “Application of linear switched reluctance motors to precision position control,” Proc. of the First International Conference on Power Electronics Systems and Applications 1:254-259, 2004.

[9] Pan, J. F. et. Al, “High-position Control of a Novel Planar Switched Reluctance Motor,” IEEE Trans. on Industrial Electronics 52(6):1644-1652, 2005.

[10] Pan, J. F. et. Al, “An auto-disturbance rejection controller for the novel planar switched reluctance motor,” IEE Proc. on Electric Power Applications 153(2):307-316, 2006.

[11] Zhao, S. W. et. Al, “Trajectory control of a linear switched reluctance motor using a Two-Degree-of-Freedom controller,” IEEE Proc. Of First International Power and Energy Conference 492-496, 2006.

[12] Vembu Gourishankar, Donald H. Kelly, “Electromechanical Energy Conversion (Second Edition),” Intext Educational Publishers, New York, 1973.