A Magnetic Levitated Switched Reluctance Motor System for High-Precision Position Control Applications

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ABSTRACT: The investigation, development and fabrication of a magnetic levitated linear motion system, based on Switched Reluctance (SR) principle for high-acceleration and high-precision position control applications, are addressed in this paper. The proposed system 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, lower manufacturing cost, and higher reliability. In this paper, the mechanical structure of the proposed levitation system and the model of the actuators are discussed. Simulation results are also performed to validate the design concept. Finally, the nonlinear force control for the magnetic levitated and propelled axes is considered so as to achieve a stable and high-precision position control

1 INTRODUCTION

Traditionally, magnetically levitated carrier systems were originally developed for the transportation systems. The most common form of this type of motor is the synchronous Long Stator Motor (LSM) with Lateral stabilization (Venkataratnam, K. & Chattopadhyay, A. B. 2002), the magnetic levitated scheme uses Active Magnetic Bearings (AMB) (Hajjaji, A. & Ouladsine, M. 2001, Komori, K. & Yamane, T. 2001), and the Permanent-Magnet (PM) linear tracks with High-Temperature Super-Conductors (HTSC) support. (Nagashima, K. et. al. 2000)

All the above methodologies will 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 sytem.

The purpose of this project is to develop a novel, high-performance, magnetic-levitated, direct-drive linear motion system for high-precision and high-speed material transport applications. The motion system is targeted for industrial automation machines. Unlike passenger transportation systems, 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.

2 THE SWITCHED RELUCTANCE (SR) MAGNETIC LEVITATED LINEAR MOTOR

Figure 1 shows the layout of the magnetic levitated SR linear actuator. It consists of a Linear Switched

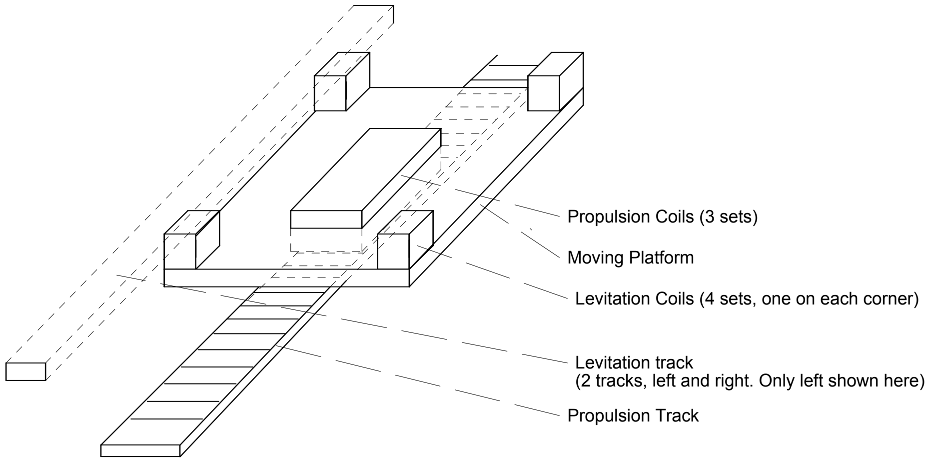

Figure 1 Layout of the Magnetic Levitated VR Linear Actuator

Reluctance Motor (LSRM) that is driven by three propulsion coils and four separated levitation coils, one on each corner of the moving platform.

Four proximity sensors are located on the four corners of the moving platform, to ensure a constant air gap between the moving platform and the track rails.

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 1.

Table 1. Motion design specifications.

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

- Notes
- An optical encoder with 1um resolution is installed in the propulsion axis.
- Four proximity position sensors are installed at the four corners of the moving platform.

3 THE FINITE ELEMENT ANALYSIS (FEA) SIMULATIONS OF THE PROPSOED ACTUTAOR

The simplified 2D drawing of the proposed actuator is shown in Figure.2. At the development stage, the total air gap length (sum of air gap 1 and 2) is fixed to 2.5 mm.

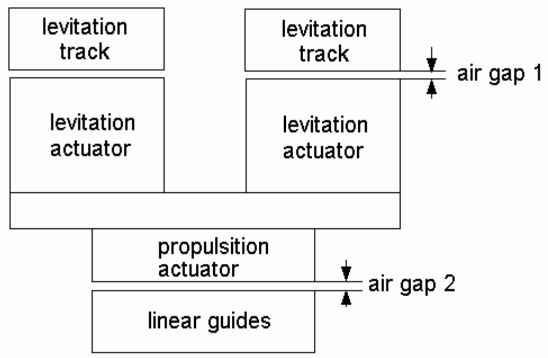

Figure 2. Side view of the proposed actuator.

3.1 Performance Prediction

To further verify the electromagnetic characteristics of the motion system, a series of finite element analysis and experiments have been carried out for both the propulsion and levitation actuators. The main goal of the design for the levitation actuators focused on the counteraction from the weight and vibrations of the moving platform. The levitation actuators are assembled in U-shape as shown in Figure 3 so as to ease the mass production.

3.3.1 Levitation Performance

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

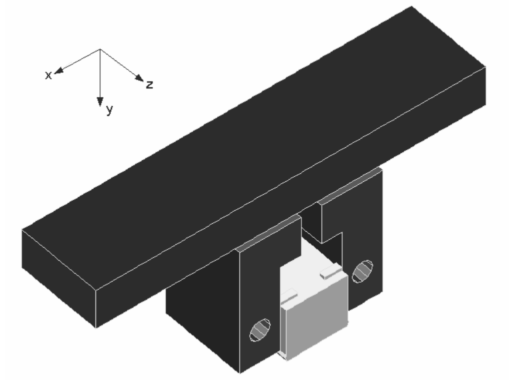

Figure 3. 3-D drawing of the levitation axis – single coil.

actuators are identical, the analysis of only one is enough. Figure 3 shows the 3D model of the levitation actuator.

The simulation takes into account of the worst cases air gap change from 0.5 mm to 2 mm; this is to test whether the four levitation actuators are capable of compensating for the attraction force generated by the bottom LSRM 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 Figure .4.

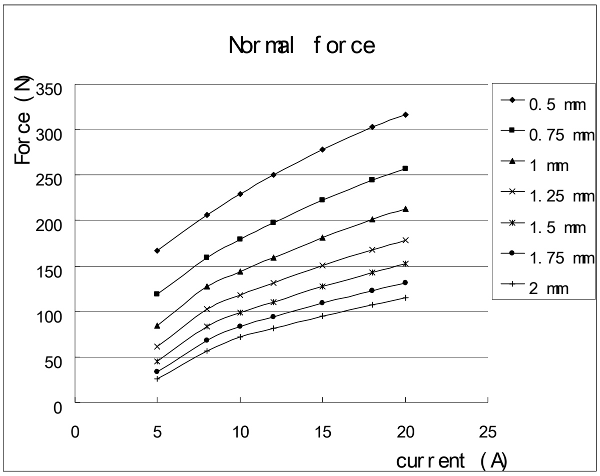

Figure 4. Normal forces of one levitation coil.

Under the worst case that the levitation air gap falls within 2 mm, four levitation actuators can produce a normal force more than 400 N altogether, which is enough to compensate the weight and normal force from the propulsion platform.

3.3.2. Propulsion Perforce

Figure 5 shows the propulsion actuator 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. Detailed results and comparisons from the experiment are shown in Figures 6-7.

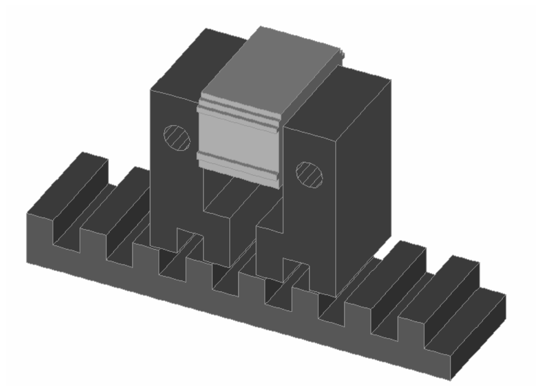

Figure 5. 3-D drawing of the propulsion axis – single phase.

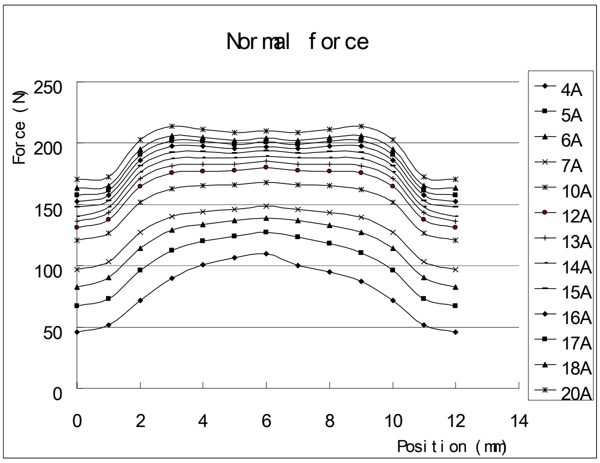

Figure 6. Normal force of the propulsion actuator.

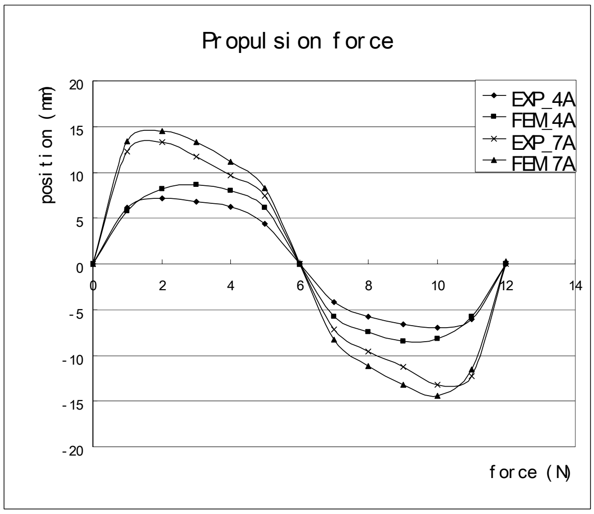

Figure 7. Propulsion force of the propulsion actuator.

4 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 Magnetic Suspension Control

The magnetic suspension control is composed of four levitation coils as shown in Figure 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. Figure 8 shows the proposed control algorithm block diagram.

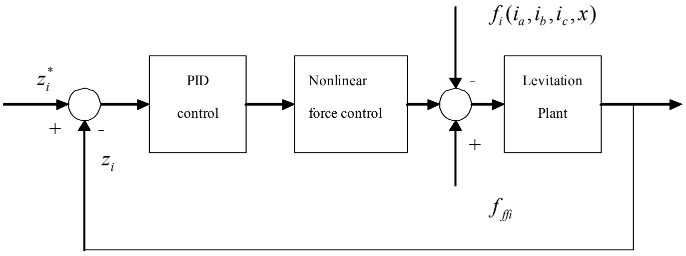

Figure 8. The control block diagram for the levitation coil – single coil.

In Figure 8, z_i^* is the levitation air gap and we set 1mm in our system, z_i is the feedback z-axis position information which is provided by a proximity analog position sensor. When we excite the bottom LSRM 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 Figure 6 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 Figure 8, can be applied to cancel the normal attraction force generated by the bottom LSRM. Finally, a consistent levitation gap can always be maintained.

For the nonlinear force control of the levitation coil, the following simple but effective current-force-position equation can be employed (Rodriguez, H. el. Al. 2000):

$$i_i^* = \sqrt{\frac{2f_i^*}{\partial L(z)/\partial z}}$$

where f_i^* is the total required force, $L(z)$ is the inductance function and i_i^* is the required current command that will be inputted to a fast dynamic current tracking loop of the individual levitation coil.

4.2 Propulsion axis control

As shown in Figure 1, the propulsion force in x-axis is generated by the bottom LSRM. The mathematical model of the LSRM for a single phase is given by (Gan, W. C. et. al. 2003a),

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

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

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

The propulsion axis force and position control of LSRMs had been developed extensively by the authors in (Gan, W. C. et. al. 2003a, Gan, W. C. & Cheung, N. C. 2003b, Gan, W. C. 2004, Pan, J. F. et. al. 2005, Pan, J. F. 2006). 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.

In summary, with the proposed magnetic and propulsion axes control, the newly developed levitation system can run in a contactless environment with the specifications given in Table 1.

5 CONCLUSIONS

A new magnetic levitated 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. On the other hand, 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 mechanical prototype of the proposed magnetic levitated actuator is under construction and the experimental results will be ready and reported soon.

In conclusion, accurate position control of SR magnetic levitated actuators is new to literature and the proposed system introduced in this paper is beneficial to precision motion control industry.

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