USING VARIABLE RELUCTANCE ACTUATION IN HIGH-PRECISION MAGNETIC LEVITATED LINEAR MOTORS – A COMPARISON STUDY

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ABSTRACT

This paper assesses the feasibility of using magnetic levitated actuators in high precision linear motion systems. This arrangement has several advantages over traditional system, including friction-free, minimal maintenance, and the elimination of expensive mechanical propulsion and guidance components. The paper first investigates existing technologies of magnetic levitation. Then it proposes a new magnetic levitation linear motor structure based on variable reluctance (VR) structure. Finally the paper performs simulations on the proposed structure and come out with some very interesting and exciting results.

KEY WORDS

Magnetic levitation, variable reluctance, linear motor, high precision.

1. INTRODUCTION

This paper describes an on-going project which aims to develop a novel, high-performance, magnetic-levitated, direct-drive linear motion system for high-precision and high-speed material transport applications. This arrangement has several advantages:

- Comparing to traditional ball-bearing guided motion systems, the proposed system has the advantages of being contact-free and contamination-free, thus resolving the problems of mechanical wear, friction, noise, heat generation, and "metal dust" contamination.
- 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).
- Mechanical couplings, lead screws, magnets, and brushes are not required. The moving element is frictionless. The degree of precision is inherent into the structure; special mechanical adjustments or alignments are not necessary. The resulting motion system is low-cost, highly robust, maintenance free, and it has less heating problems.

2. EXISTING TECHNOLOGIES

Traditionally, magnetically levitated carrier systems were originally developed for the transportation system [1,4,6,11,17,18,19,20].

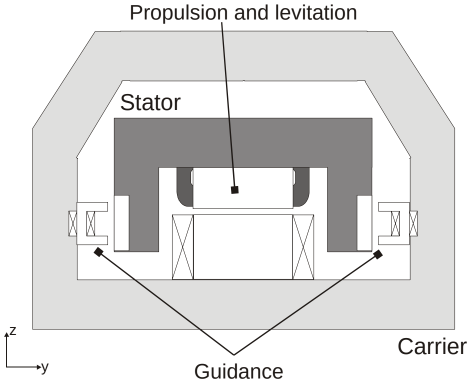

Fig 1 Magnetic Suspension with LSM and lateral stabilization

The most common form of this type of motor is the Synchronous Long Stator Motor (LSM) with Lateral Stabilization [1], as shown in Fig. 1. Through the motor configuration has reached mature state, there are still many aspects under research. On one hand, further optimization of the magnetic circuit, taking into account the strong coupling among the windings, is now possible by using numerical techniques [2]. On the other hand, the improvement of the control strategies for electromagnetic bearings has also received great attention. In [3] and [4] two novel self-sensing bearings based on current measurements are proposed, while an alternative strategy, which uses the inductance measurement principle is presented in [5]. However, these methods have been only applied to rotating magnetic bearings.

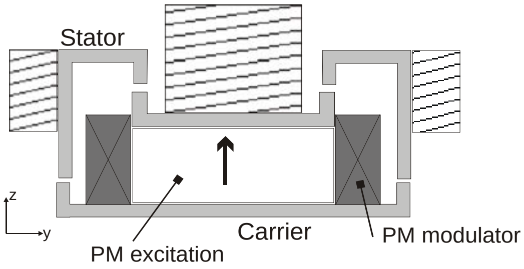

Fig. 2 PM Excitation & DC Control Windings

Fig. 2 shows another magnetic levitated scheme uses Active magnetic bearings (AMB) [6,7], which is based on the interaction between an iron stator and the controlled electromagnets attached to the suspended body, which enable the integration of the support and the guidance functions. A large number of AMB applications have been reported during the last few years, especially in the fields of turbo-machinery [8, 9] and flywheel energy storage [10]. An early example of levitated carrier with AMBs can be found in [11].

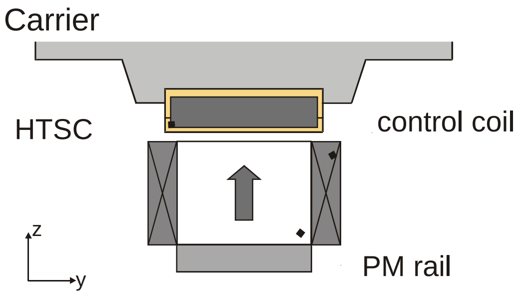

Fig. 3 Support and Guidance with HTSC and Controlled PM

Recently, there have been new researches in using very expensive permanent-magnet (PM) rails and high-temperature super-conductors (HTSC) as the linear magnetic bearings [12, 13] (see Fig. 3). However, very few prototypes of linear bearings with HTSC bulks have been developed until now. A carrier platform to move silicon wafers was designed and built up by the Japanese firm Toshiba in the early 90's [14]. The carrier, with a total weight of 1.3 kg, contained several HTSC pellets, which provided the stable levitation in interaction with the PMs of the guide way. Recently, there were a few examples of demonstrating the use of HTSC in model train transport in China, Japan [15], and the United States. On the other hand, researchers started to perform research on precision position control for magnetic levitated motor but the present of PM is the basic requirement in their design [21,22].

To summarize, all the above technologies are primarily developed for transportation use [16]. All the above methodologies will produce sophisticated magnetic levitation systems that are efficient, but difficult to manufacture and complex to control. In addition, the employment of rare-earth permanent magnet and high temperature superconductor produces additional manufacturing and maintenance problems to the system.

3. THE MAGNETIC LEVITATED VR ACTUATOR

In this paper, a novel construction topology of magnetic levitated linear motor is proposed. The motor's structure is based on transverse flux motor (TFM) topology and the forces are derived from variable reluctance (VR) principle. A similar structure can be found in [30,31,32]; however, their application only concentrates on speed control for transportation system while our proposed system targets at high acceleration/deceleration and accurate position control application. Owing to the unique structure of the magnetic levitated VR linear motor (VRLM), the propulsion, suspension and guidance forces are integrated together, and can be controlled through the two pairs of three phase coils in the motor. Fig. 4 shows the three dimensional (3D) view, the front view, and the side view of the motor. Fig. 5 shows the position of the three-phase coils pair in the motion system.

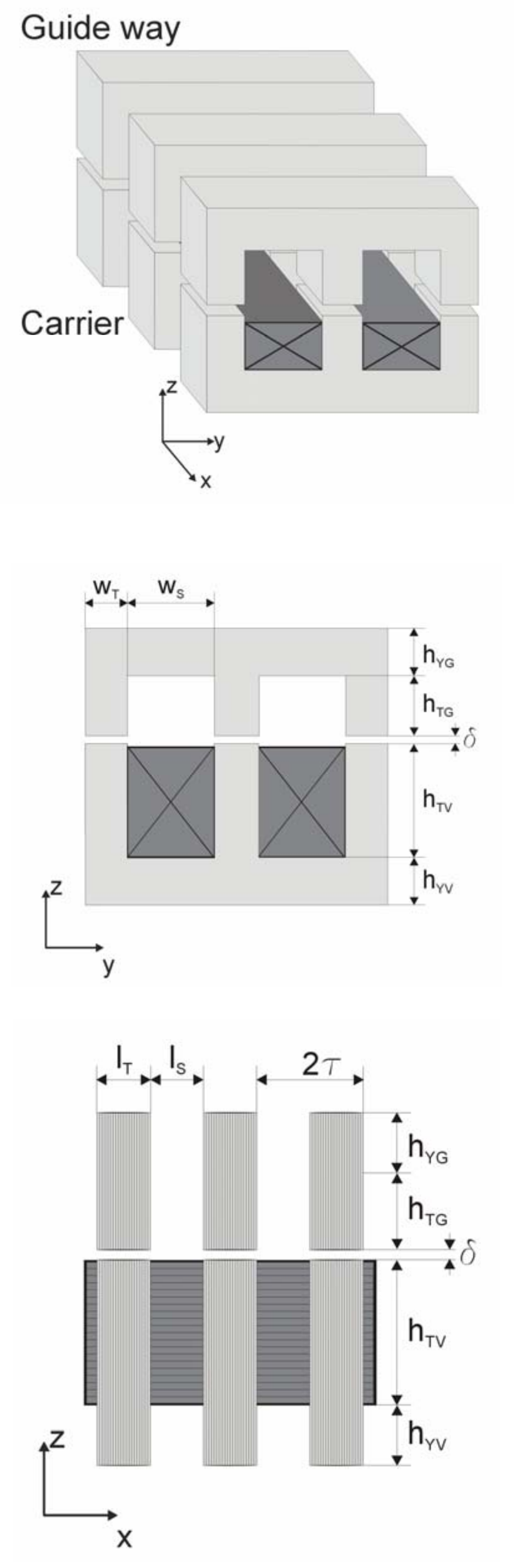

Fig. 4 3-D view, front view, and side view of the Single Phase TFM

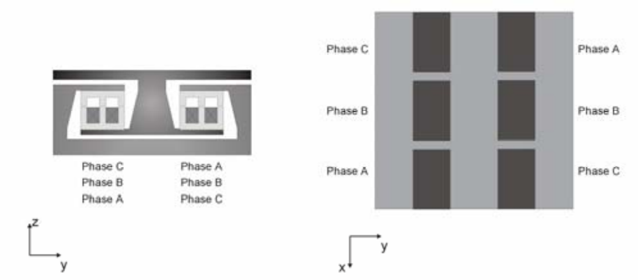

Fig. 5 Levitated carrier in a TFM-321 configuration

4. RESULTS OF SIMULATION

The proposed structure was simulated using a Finite Element Analysis package MEGA, and the results are shown in Figs 6-8.

The results indicate that the actuator is inherently stable in the Y direction, but unstable in the z direction. Fig. 9 also indicates that the traction force is nonlinear along the X direction of the motor. It also contains a z force-ripple component. To summarize, the proposed structure has a very simple and robust construction. However, in order to control the actuator properly, an intelligent multi-dimensional controller has top be employed.

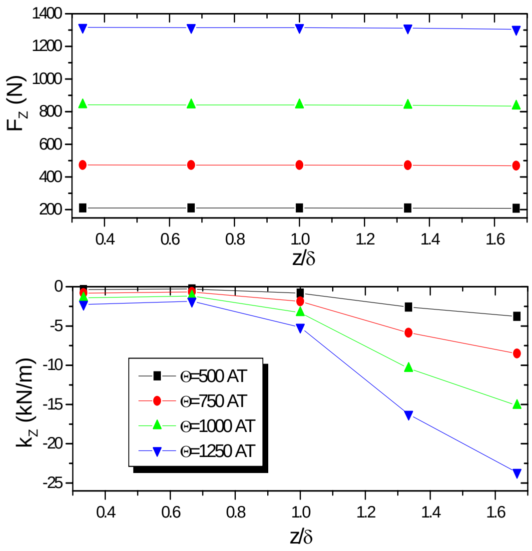

Fig. 6 Support force and stiffness as a function of as function of z/δ

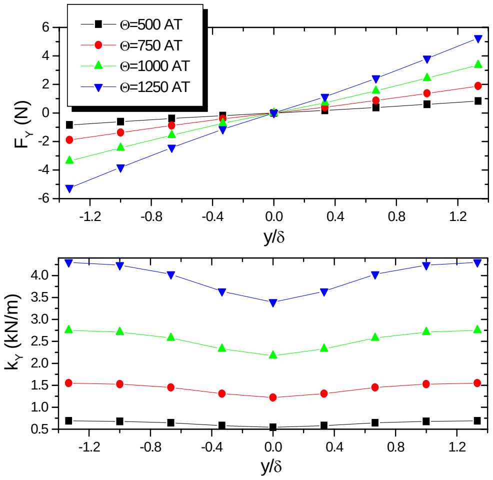

Fig. 7 Guidance force and stiffness as function of y/δ

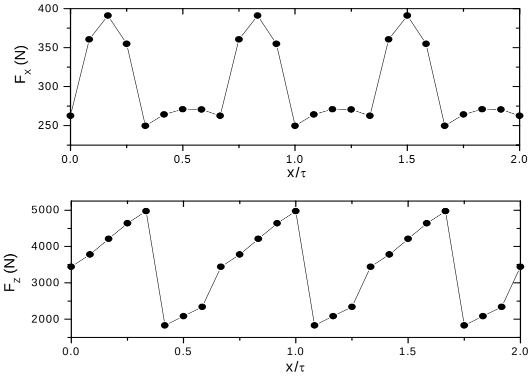

Fig. 8 Traction and support forces (F_X, F_Z) as function of x/τ

3. CONCLUSION

To conclude, the proposed VR magnetic levitated linear actuator it is easy to fabricate, and the mechanical hardware is far less complicated than traditional arrangements. Moreover, the manufacturing cost is low, because the motor does not require any magnets or superconductor components. However, in order to control the actuator properly, an intelligent multi-input multi-output controller robust controller has to be employed.

4. ACKNOWLEDGEMENT

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REFERENCES

[1] K. Venkataratnam and A.B. Chattopadhyay, "Analysis of electromagnetic forces in a levitated short rotor LIM ," *IEEE Trans. on Energy Conversion*, Vol. 17, No. 1, pp. 95-106, Mar. 2002.

[2] M. Andriollo, G. Martinelli, A. Morini, and A. Tortella, "FEM calculation of the LSM propulsion force in EMS-MAGLEV trains," *IEEE Trans. on Magnetics*, Vol. 32, No. 5, pp. 5064-5066, Sep. 1996.

[3] D. Vischer and H. Bleuler, "Self-sensing active magnetic levitation," *IEEE Trans. on Magnetics*, Vol. 29, No. 2, pp. 1276-1281, Mar. 1993.

[4] Y.K. Tzeng and T.C. Wang, "A novel compensating approach for self-sensing Maglev system with controlled-PM electromagnets," *IEEE Trans. on Magnetics*, Vol. 31, No. 6, pp. 4208-4210, Nov. 1995.

[5] K.K. Sivadasan, "Analysis of self-sensing active magnetic bearings working on inductance measurement principle," *IEEE Trans. on Magnetics*, Vol. 31, No. 2, pp. 329-334, Mar. 1996.

[6] A. El Hajjaji and M. Ouladsine, "Modeling and nonlinear control of magnetic levitation systems," *IEEE Trans. on Industrial Electronics*, Vol. 48, No. 4, pp. 831-838, Aug. 2001.

[7] K. Komori and T. Yamane, "Magnetically levitated micro PM motors by two types of active magnetic bearings," *IEEE/ASME Trans. on Mechatronics*, Vol. 6, No. 1, pp. 43-49, Mar. 2001.

[8] M. Antilla, E. Lantto, J. Saari, H. Esa, O. Lindgren and K. Säily, "Design of water treatment compressors equiped with active magnetic bearings," *Proc. of the 5th Internation Symposium on Magnetic Bearings*, Kanszawa (Japan), 1996.

[9] W. R. Canders, "High-speed machines on magnetic bearings – Design concepts and power limits," *Proc. of the International Conference on Electric Machines*, Istanbul (Turkey), 1998.

[10] H. Weh et al., "Magnetically levitated flywheel energy storage system with integrated energy converter," *Proc. of the International Conference on Electric Machines*, Vigo (Spain), 1996.

[11] M. Morishita et al., "A new Maglev system for magnetically levitated carrier system," *IEEE Trans. on Vehicular Technology*, Vol. 38, No. 4, pp. 230-236, Nov. 1989.

[12] K. Nagashima, Y. Iwasa, K. Sawa, and M. Murakami, "Controlled levitation of bulk superconductors," *IEEE Trans. on Applied Superconductivity*, Vol 10, No.3, pp. 1642-1648, Sep. 2000.

[13] K. Nagaya, T. Suzuki, N. Takahashi, and H. Kobayashi, “Permanent magnet pulse motor with high temperature superconducting levitation,” *IEEE Trans. on Applied Superconductivity*, Vol. 11, No. 4, pp. 4109-4115, Dec. 2001.

[14] T. Azukizawa, M. Morishita, N. Kasahara, M. Akoshi, and H. Ogiwara, “Characteristics of magnetic suspension system using high Tc superconductors,” *Proc. of the International Symposium on Non-linear Phenomena in Electromagnetic Fields*, Nagoya (Japan), 1992.

[15] M. Ono, S. Koga, and H. Ohtsuki, “Japan’s superconducting maglev train,” *IEEE Instrumentation & Measurement Magazine*, Vol 5, No. 1, pp. 9-15, Mar. 2002.

[16] K. Yoshida, H. Takami, X. Kong, and A. Sonoda, “Mass reduction and propulsion control for a permanent-magnet linear synchronous motor vehicle,” *IEEE Trans. on Industry Applications*, Vol. 37, No. 1, pp. 67-72, Jan./Feb. 2001.

[17] C. T. Liu and N. Sheu, “Optimal pole arrangement design of a linear switched-reluctance machine for magnetic levitation and propulsion system,” *IEEE Trans. on Magnetics*, Vol. 32, No. 5, pp. 5067-5069, Sep. 1996.

[18] C.T. Liu, K.S.Su, and J. W. Chen, “Operational stability enhancement analysis of a transverse flux linear switched-reluctance motor,” *IEEE Trans. on Magentics*, Vol. 36, No. 5, pp.3699-3702, Sep. 2000.

[19] C. T. Liu, K.S. Su, and M. H. Lee, “Three-dimensional field and side-force design analysis of a transverse flux linear switched-reluctance machine,” *IEEE Trans. on Magnetics*, Vol. 34, No. 4, pp. 2132-2134, Jul. 1998.

[20] H. Y. Bae, B. S. Lee, P. Vijayraghavan, and R. Krishnan, “A linear switched reluctance motor: converter and control,” *IEEE Trans. on Industry Applications,* Vol. 36, No. 5, pp. 1351-1359, Sep./Oct. 2000.

[21] W. J. Kim, D. L. Trumper, and J. H. Lang, “Modeling and vector control of a planar magnetic levitator,” *IEEE Trans. on Industry Applications,* Vol. 34, No. 6, pp. 1254-1262, Nov./Dec. 1998.

[22] S. Verma, W. J. Kim, and J. Gu, “Six-axis nanopositioning device with precision magnetic levitation,” *IEEE/ASME Trans. on Mechatronics*, Vol. 9, No. 2, pp. 384-391, Jun. 2004.