A. Heya, Y. Nakata, K. Hirata and H. Ishiguro, "A Magnetically Levitated Lead Screw for Complete Non-Contact Power Transmission," IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society, Lisbon, Portugal, 2019, pp. 846-849, doi: 10.1109/IECON.2019.8927701.

A Magnetically Levitated Lead Screw for Complete Non-Contact Power Transmission

Akira Heya
Department of Adaptive Machine Systems
Osaka University
Suita, Osaka, Japan
akira.heya@ams.eng.osaka-u.ac.jp

Yoshihiro Nakata
Department of System Innovation
Osaka University
Toyonaka, Osaka, Japan
nakata@irl.sys.es.osaka-u.ac.jp

Katsuhiro Hirata
Department of Adaptive Machine Systems
Osaka University
Suita, Osaka, Japan
k-hirata@ams.eng.osaka-u.ac.jp

Hiroshi Ishiguro
Department of System Innovation
Osaka University
Toyonaka, Osaka, Japan
ishiguro@irl.sys.es.osaka-u.ac.jp

***Abstract*—Magnetic lead screw (MLS) is a feed screw that allows non-contact power transmission. The MLSs have some advantages such as reduction of particle emission and improving positioning accuracy. However, conventional MLSs need a supporting mechanism using linear guides or slide bearings. They deteriorate the advantages of MLSs because of friction. In order to solve this problem, we propose a magnetically levitated lead screw (MLLS) for complete non-contact transmission. The proposed magnetic structure and operating principle are verified through a three-dimensional finite element method. The suspension force, thrust, and torque characteristics are investigated, and the effectiveness of the MLLS are clarified.**

***Keywords*— Magnetic lead screw, Magnetic levitation, Non-contact power transmission**

I. Introduction

Magnetic lead screw (MLS) transmits forces without contact between nut and screw [1-3]. The transfer of force via magnetic fields facilitates high drive efficiency and reduction of particle emission. Therefore, MLSs suitable an environment which is required cleanness. In addition, they are expected to achieve improving positioning accuracy because of no friction losses.

Several types of MLSs have been proposed and developed [4-8]. However, they need a supporting mechanism such as linear guides or slide bearings. Therefore, a complete non-contact power transmission using MLS is not achieved. In order to solve this problem, we proposed a magnetically levitated lead screw (MLLS) which is integrated with a magnetic bearing.

This paper describes a MLLS for complete non-contact power transmission. The MLLS can hold a rotational screw made of magnetic material, and converts rotation into linear motion. The suspension force and thrust characteristics are calculated by a magnetic field analysis using a three-dimensional finite element method (3-D FEM) to confirm the feasibility of the proposed structure.

II. Design Concideration

This section describes a schematic of magnetically levitated propulsion system. In this paper, the magnetic structure and the operating principle of the MLLS in the system are proposed.

A. Magnetically Levitated Propulsion System

A schematic of a magnetically levitated propulsion system is shown in Fig. 1. The system consists of MLLS and a rotary motor which is used by a direct drive. The moving part of the system is integrated as a screw of the MLLS. A torque for rotating screw is generated by the coils of the rotary motor and converts to thrust for propulsion by the MLLS. A suspension force for levitating screw is generated by the coils of the MLLS. The MLLSs are arranged between both ends of the rotary motor.

B. Target Specification for MLLS

The target specifications of the MLLS are as follows:

- The MLLS can generate a magnetic attraction force for levitating the mover with low power consumption.
- The magnetic structure consists of axially magnetized permanent magnets with a simple shape and a few components.

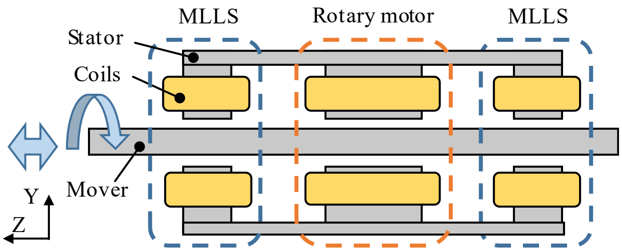

Fig. 1. Schematic of the magnetically levitated propulsion system.

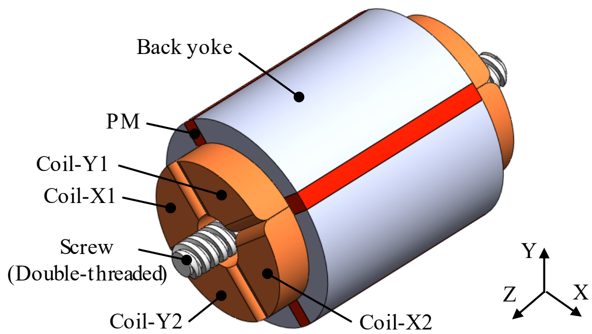

Fig. 2. Overview of the MLLS.

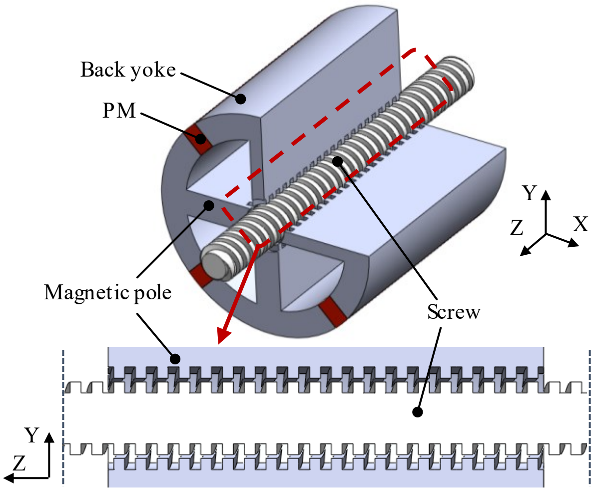

Fig. 3. Basic structure except for the coils.

C. Proposed Structure

Figure 2 shows an overview of the MLLS. The basic structure is shown in Fig.3. The stator of the MLLS consists of coils, axially magnetized permanent magnets with rectangle shape, and magnetic poles, and back yoke. The magnetic pole has a spiral groove. The screw is made of a magnetic material. Commonly-used machine screws are also applicable.

The MLLS supports the screw by a magnetic attraction force which is given by permanent magnets and electromagnets. From this hybrid supporting mechanism, it is expected that excellent controllability and low power consumption.

D. Operating Principle

The supporting principle of the MLLS is shown in Fig. 4(a). The magnetic flux generated by permanent magnets of the stator through the surface of the magnetic pole and screw thread, and constitutes bias magnetic circuit. When a current applies to the coil-X1 and coil-X2, the magnetic attraction force in the X-direction is generated because of an unbalance of the magnetic flux density. Similarly, the magnetic attraction force in the Y-direction is generated by applying the coil-Y1 and coil-Y2. The MLLS uses these attraction force as the suspension force.

The increasing principle of the bias magnetic flux is shown in Fig. 4(b). The thrust is generated by the magnetic phase difference between the stator and the screw, which is induced by the linear and angular displacement of the MLLS. When the magnetic phase difference is zero, the rotational angle θ and displacement p of the screw are defined as follows:

$$\theta = \frac{2\pi}{L} p \tag{1}$$

where L is the lead of the screw. When an external force works to the screw, the against force occurs by the relative displacement. Therefore, the screw generates spiral motion.

The control force F_c is calculated as follows:

$$F_c = F_o - F_d \tag{2}$$

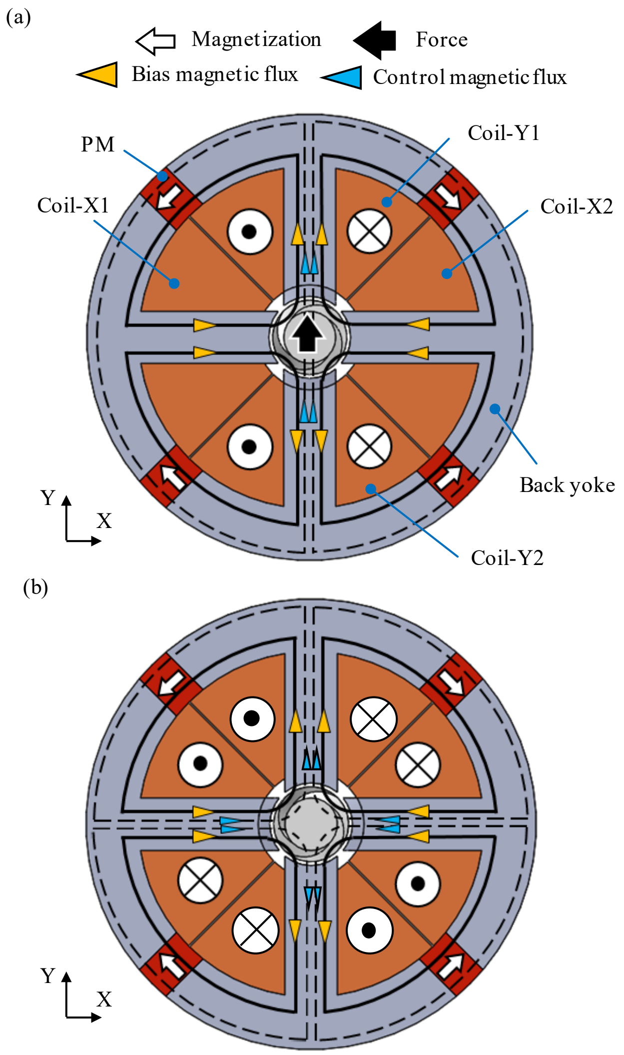

Fig. 4. Operating principle of the MLLS. (a) Suspension force. (b) Bias magnetic flux.

where F_o is the output force, F_d is the detent force. The suspension force for attracting to the center position can express as follows:

$$F_s = -F_c \tag{3}$$

The net suspension force F_{ns} is given as follows:

$$F_{ns} = F_s - F_d - F_{mg} \tag{4}$$

where F_{mg} is the force caused by gravity for the weight of the screw.

III. Static Characteristics

The suspension force, thrust, and torque of the MLLS are calculated, and the conditions and results of the magnetic field analysis using 3-D FEM are presented.

A. Analysis Conditions

The design parameters of the MLLS are shown in Fig. 5. The parameter values are listed in Table I. The analysis conditions of

3-D FEM are listed in Table II. The 3-D mesh model excepts for the air region is shown in Fig. 6. The magnetic poles, back yoke, and screw were made of soft magnetic material. The residual magnetic flux density of the permanent magnets was 1.3 T, and the coercive force was 1.05×10^{6} A/m. A current of 10 A was applied to the coils. The mass of the screw is 48.8 g.

The suspension force was calculated under screw rotation and Y-direction displacement while the stator was fixed. Similarly, the thrust was evaluated under screw rotation at the center position.

B. Results

The magnetic flux density vector distributions when non-excited and excited state are shown in Fig. 7. From Fig. 7(a), the bias magnetic circuit is constituted by the magnetic flux generated by the permanent magnets. From Fig. 7(b), it is found that the unbalance of the magnetic flux density is generated by the exciting Coil-Y1 and -Y2.

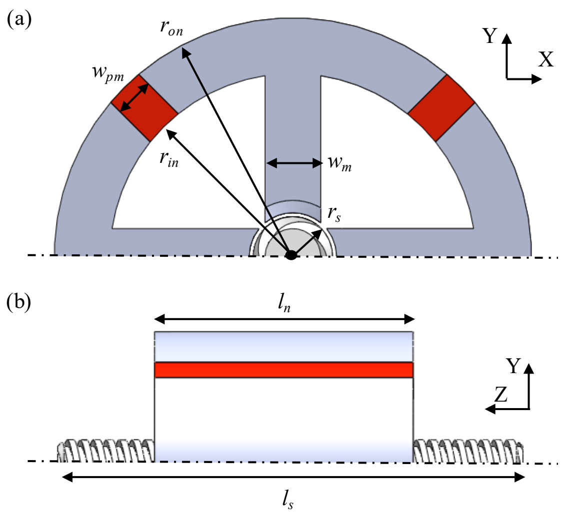

Fig. 5. Design parameters of the MLLS. (a) Cross-sectional view in the X-Y plane. (b) Side view.

TABLE I. DIMENSIONS OF THE MLLS

Symbol	Quantity	Value
r_{on}	Outer radius of the stator	30.0 mm
r_{in}	Inner radius of the stator	23.0 mm
r_s	Radius of the screw	5.0 mm
w_m	Width of the magnetic pole	13.9 mm
w_{pm}	Width of the permanent magnet	5.0 mm
l_n	Length of the stator	60.0 mm
l_s	Length of the screw	108.0 mm
L	Lead of the screw	6.0 mm
	Pitch of the screw	3.0 mm
	Air gap	0.5 mm

TABLE II. ANALYSIS CONDITIONS OF THE 3-D FEM

Number of elements	1,639,788
Number of nodes	283,185
Calculation time	15 min/step
CPU	Intel(R) Core(TM) i7-5930K

The analysis results of the control force and the detent force are shown in Fig. 8. The comparison of the suspension force and the detent force are shown in Fig. 9. The maximum and minimum suspension force were 295.5 N and 128.8 N, respectively. Moreover, The suspension force was changed by rotating the screw.

The analysis results of the net suspension force are shown in Fig. 10. The net suspension force was positive value in all region. The maximum and minimum net suspension force were 201.3 N and 84.6 N, respectively.

The analysis results of the thrust and torque are shown in Fig. 11. The maximum thrust and torque were 35.9 N and 34.5 mNm, respectively. The thrust and torque increased by applying a current to the coils.

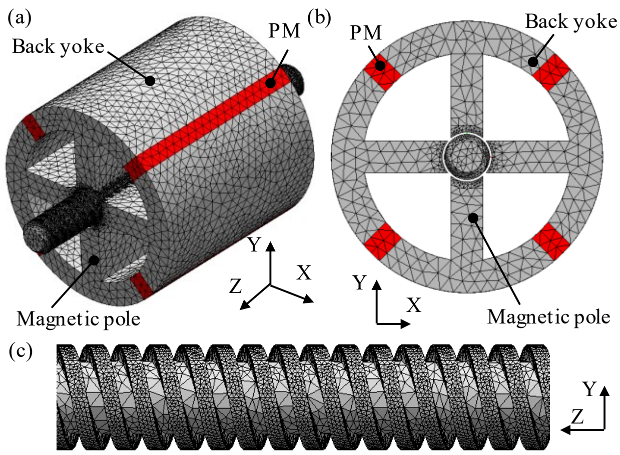

Fig. 6. Mesh model except for the air region and coils. (a) Whole view. (b) Cross-sectional view in the X-Y plane. (c) Screw.

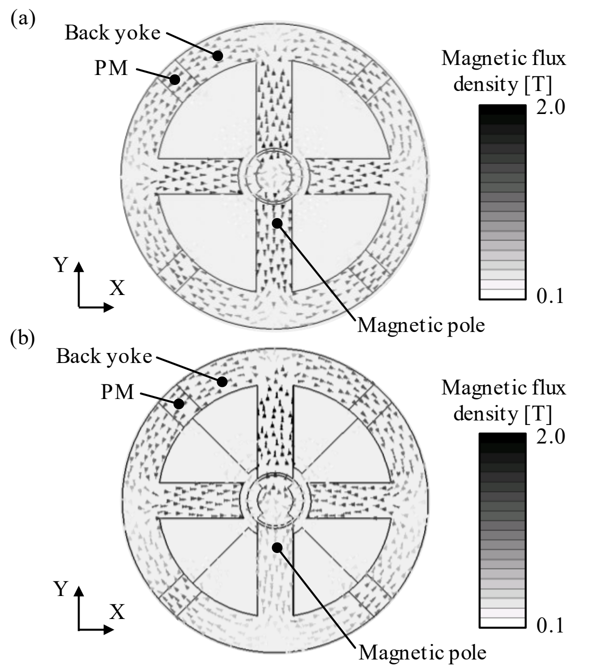

Fig. 7. Analysis results of the magnetic flux density vector. (a) Non-excited state. (b) Excited the Coil-Y1 and -Y2.

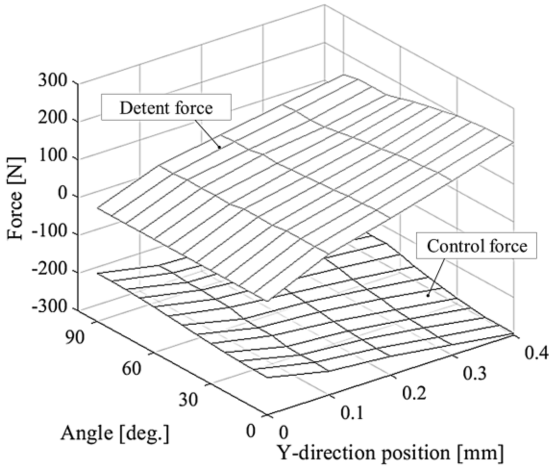

Fig. 8. Analysis results of the control force and the detent force.

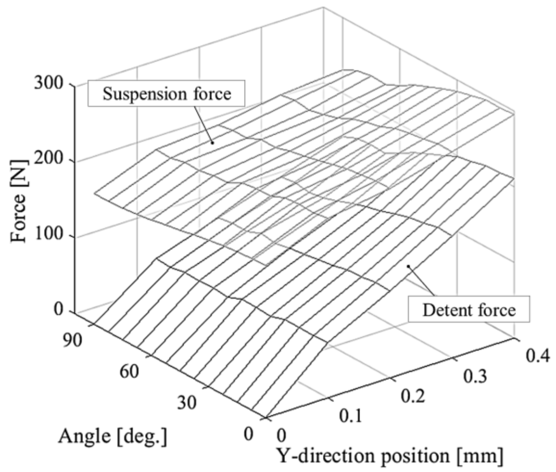

Fig. 9. Comparison of the suspension force and detent force.

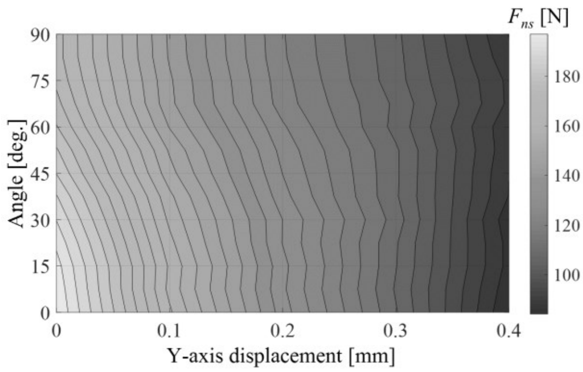

Fig. 10. Analysis results of the net suspension force.

C. Discussion

The net suspension force was positive in the all movable range. This shows that the MLLS can levitate the screw under considering a gravity from the screw weight.

The variation of suspension force under screw rotation was generated because of changing the facing areas between the magnetic poles and screw threads. An increase of the thrust and torque when exciting the coils was occurred by increasing bias magnetic flux.

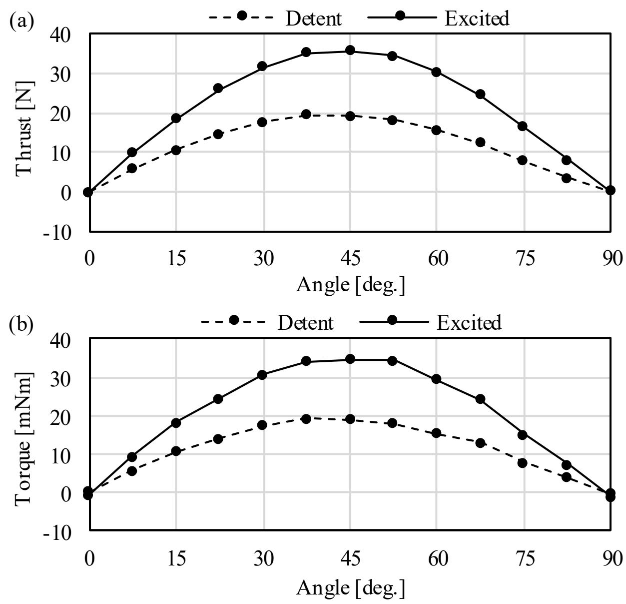

Fig. 11. Analysis results of the thrust and torque. (a) Thrust characteristics. (b) Torque characteristics.

IV. Conclusion

This paper described the MLLS for complete non-contact power transmission. From the analyzed results of the net suspension force, it is clarified that the MLLS can levitate the screw under considering gravity from the screw weight. Moreover, the thrust characteristics can be improved by the exciting coils because of the increase of bias magnetic flux. In future work, a rotary motor is integrated with the MLLS.

References

[1] J. Wang, K. Atallah, and W. Wang, “Analysis of a Magnetic Screw for High Force Density Linear Electromagnetic Actuators,” IEEE Trans. Magn., vol. 47, no. 10, pp. 4477-4480, Oct. 2011.

[2] S. Pakdelian, N. W. Frank, and H. A. Toliyat, “Principles of the Trans-Rotary Magnetic Gear,” IEEE Trans. Magn., vol. 49, no. 2, pp. 883-889, Feb. 2013.

[3] Z. Ling, W. Zhao, J. Ji, and G. Liu, ”Design of a New Magnetic Screw With Discretized PMs,” IEEE Trans. Appl. Supercond., vol. 26, no. 4, 0602805, June 2016.

[4] R. J. A. Paul, ”Magnetic rotary-linear or linear-rotary convertor,” *IEE J. Electric Power Appl.*, vol. 2, no. 4, pp. 135-138, Aug. 1979.

[5] N. I. Berg, R. K. Holm, and P. O. Rasmussen, “Theoretical and Experimental Loss and Efciency Studies of a Magnetic Lead Screw, ” IEEE Trans. Appl., vol. 51, no. 2, pp. 1438-1445, Mar./Arp. 2015.

[6] S. Pakdelian, Y. B. Deshpande, H. A. Toliyat, “ Design of an Electric Machine Integrated with Trans-Rotary Magnetic Gear, ” IEEE Trans. Ind. Energy Convers., vol. 30, no. 3, pp. 1180-1191, Sep. 2015.

[7] Z. Ling, J. Ji, J. Wang, and W. Zhao, “Design Optimization and Test of a Radially Magnetized Magnetic Screw With Discretized PMs,” IEEE Trans. Ind. Electron., vol. 65, no. 9, pp. 7536-7547, Sept. 2018.

[8] A. Heya, Y. Yoshihiro, M. Sakai, H. Ishiguro, K. Hirata, “Force Estimation Method for a Magnetic Lead-Screw-Driven Linear Actuator,” *IEEE Trans. Magn.,* Vol. 54, no. 11, Nov. 2018.