# MAGNETIC LEAD SCREW MECHANISM AND ITS APPLICATION TO LINEAR POSITIONING SYSTEM

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## ABSTRACT

In this paper, first, a new type of magnetic lead screw mechanism (MLSM) which is comprised of a conventional steel lead screw and a nut of permanent magnet is proposed. To analyze basic characteristics, experimental MLSMs are made, and the flux density of a magnetic nut and the axial carrying load of the MLSMs are measured and simulated. Finally, to evaluate the effectiveness of the MLSM as a machine element, a linear positioning system which consists of the MLSM, a linear motion air guide and a brushless DC servomotor is constructed. Experimental results prove that the positioning system using the MLSM with an appropriate feedback system can work well as those using ball lead screw mechanisms or air lead screw mechanisms.

## INTRODUCTION

A lead screw mechanism is one of basic mechanical elements that are used not only to transmit force but also to position objects. In the positioning systems, ball lead screw mechanisms (BLSM) are widely used in industrial machinery and precision machines [1]. The BLSMs are not suitable for the use in a clean room because the wear particles and lubricant pollute the clean environment. The use of the BLSMs in a vacuum or space also causes lubrication problems.

Authors had proposed an air lead screw mechanism (ALSM) which is characterized by no mechanical contact and high accuracy [2]. Although the ALSM can be used for semiconductor processes in the clean room, they can't be used in a vacuum. Instead of the lead screw mechanisms, linear motors can work well in a vacuum, but the motor coils generate heat causing the thermal deformation of the mechanical structure which is not preferable for precision machines because the positioning and motion accuracy might be decreased.

To solve above-mentioned problems, a lead screw mechanism of noncontact, small heat generation and no air consumption type is necessary. Magnetic lead screw mechanisms (MLSMs) are noncontact ones which transmit driving forces from screws to nuts with magnetic couplings so that they are free from the friction and lubrication problems. Not only they can be used in a vacuum, they do not make noise and vibration.

Some types of magnetic lead screws were introduced [3]. Their structures were too complicated to be produced practically. Further their axial stiffness and load capacity were smaller than those of BLMSs and ALSMs, because the stiffness and load capacity of the magnetic couplings were generally lower than those of the steel balls and air films.

In this paper, first, a new type of MLSM which consists of a steel lead screw and a magnetic nut is proposed. Secondary, an optimum geometrical profile to give the maximum load capacity and stiffness is discussed through simulations and experiments. Finally, to evaluate the effectiveness of the MLSM as a machine element, a liner positioning systems using the MLSM is constructed and its positioning accuracy and compliance characteristics are experimentally examined.

## PRINCIPLE OF PROPOSED MLSM

Figure 1 shows the principle of a proposed MLSM. A screw is conventional steel one of double square threads. A cy-

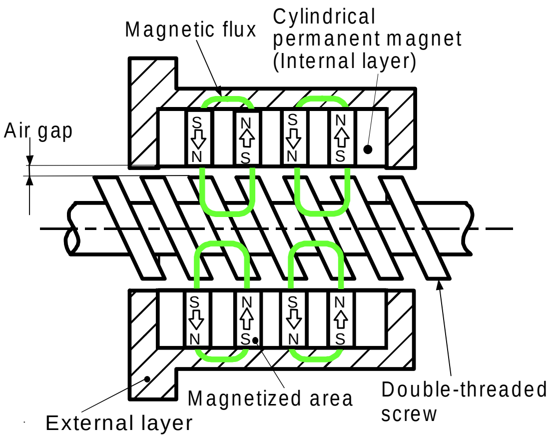
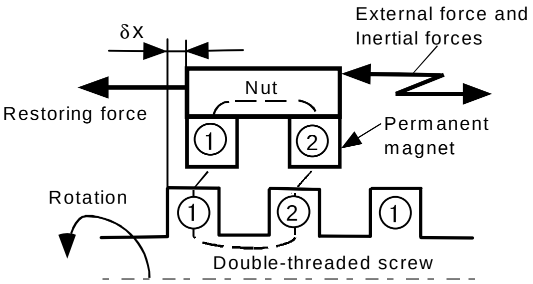
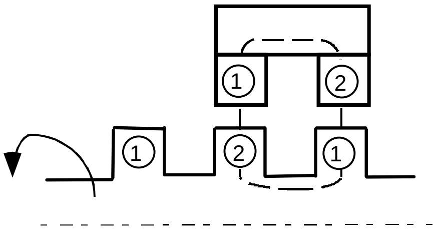


**FIGURE 1**: Principle of a proposed MLSM



(a) Synchronism



(b) Out-of-step

**FIGURE 2**: Synchronism and out-of-step

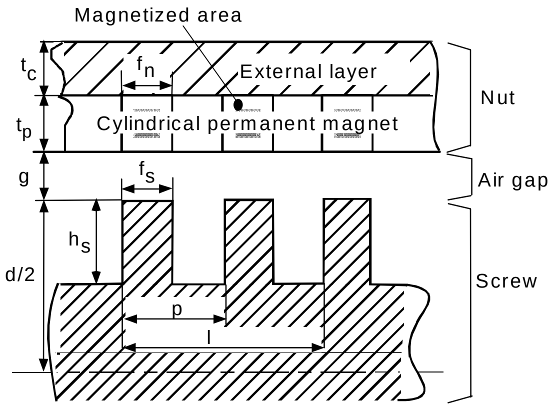


**FIGURE 3**: Profile of MLSM

lindrical nut has two layers. The internal layer is cylindrical permanent magnet which is double-helically magnetized and the external one is made of steel so as to work as a yoke. The structure is simple and is easy to be manufactured. Magnetic flux lines starting from magnetized areas show magnetic circuits which function as magnetic couplings.

As shown in Figure 2 (a), the relative displacement ($\delta x$) between the screw and nut generates an axial restoring force. The force drives the nut along the screw as long as the external force or inertial force under acceleration does not exceed the maximum restoring force of the magnetic couplings. Once either external or inertial force exceeds the maximum restoring force, the out-of-step happens and the nut jumps to the next teeth as shown in Figure 2 (b).

It is important to increase not only the maximum restoring force but also the amount of the restoring force to the unit displacement (stiffness) because the larger restoring force and stiffness make the possible starting up accelerations and the driven mass larger. In this paper, the restoring force is called the transmitting load.

## EXPERIMENTAL MLSM

### MLSM Prototype

To clarify the static characteristics such as the axial transmitting load and stiffness, an experimental MLSM in Figure 3 and Table 1 is produced. The internal nut is made of anisotropic permanent magnets, which are neodymium-iron-boron ones ($Nd_2Fe_{14}B$, Br=1.12-1.20 T, ${}_bH_c$=844-923 kA/m). The nut is double-helically magnetized by a special electromagnet which is made of a steel screw and wound coils around the screw threads. The nut and screw are made of S25 and SCM445 steel respectively. Figure 4 shows a cutaway of the experimental MLSM.

### Analytic Model of MLSM

The finite element method (FEM) software for magnetic analysis (Photon, Eddy2D) is used to simulate flux density distribution and magnetic force, because the FEM software can precisely evaluate the permeance between the screw and nut under various relative displacement conditions. One of the FEM models for simulating transmitting load is shown in Figure 5. The axisymmetric model which does not take a lead angle of the screw and nut into consideration is adopted to reduce the modeling and calculating time.

### Flux Density Measurement of Magnetic Nut

To evaluate the magnetization of the nut, the magnetic flux

**TABLE 1**: Experimental magnetic lead screw

| | | | |
|---|---|---|---|
| Nut | $t_c$ | external layer thickness | 5.0mm |
| | $t_p$ | magnet thickness | 2.5mm |
| | $f_n$ | magnetized width | 2.5mm |
| | N | number of double-thread turns | 5 |
| Screw | d | diameter | 25.0mm |
| | $h_s$ | thread depth | 4.0mm |
| | $f_s$ | flat width | 2.5mm |
| | p | pitch | 5.0 mm |
| | l | lead | 10.0mm |
| | g | gap | 0.1mm |

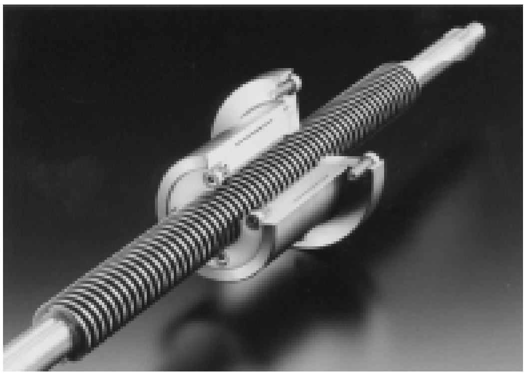


**FIGURE 4**: Photograph of the cutaway MLSM

density distribution over the internal nut surface without the screw is measured. Figure 6 shows the measurement setup. The radial flux density is measured by the gauss probe which is moved in the axial line at a height of 1.5 mm from the internal nut surface. Figure 7 shows the measured and simulated results of the flux density distribution. The simulation was made over 6 threads. The flux density distribution along the axis is sinusoidal. 780 kA/m magnetic coercive force of the nut is identified from the experimental data. The identified coercive force is smaller than that of the technical data (bHc=844-923 kA/m) by the manufacture. The difference between identified and technical data is caused by the insufficient magnetization in the rectangle magnetized areas as shown in Figure 3. The profile optimization of the electromagnet for magnetizing the nut and the increase of the magnetizing current should improve the magnetic flux density strength of the nut to the technical data.

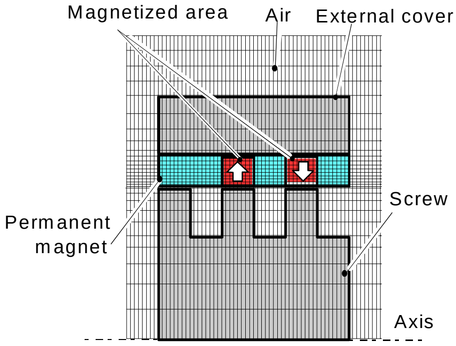


**FIGURE 5**: Axisymmetric model for analyzing flux density and axial transmitting force (lead angle is not considered)

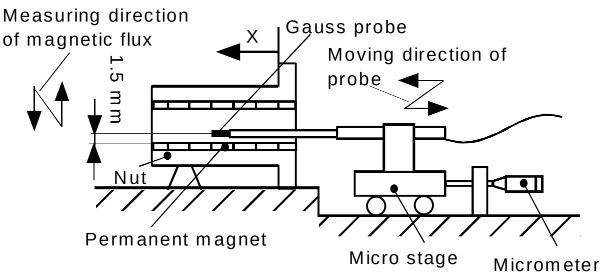


**FIGURE 6**: Flux density measurement over the internal surface of the magnetic nut

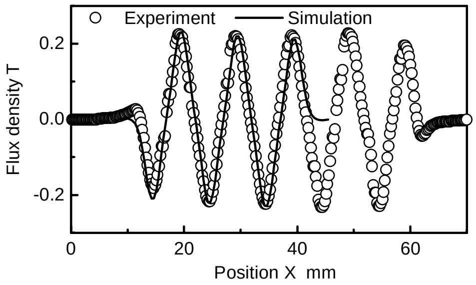


**FIGURE 7**: Flux density over the internal nut surface (Experiment and simulation)

### Axial Transmitting Load Measurement

Figure 8 shows the setup of the axial transmitting load measurement. The nut and screw are fixed on the base except axial translation freedom of the screw. A pair of guide rings made of polyimide resin are set at the both ends of the nut to keep a 0.1 mm clearance between the nut and screw. The axial force is applied to the edge of the screw by a tailstock with a load cell. The force and displacement are measured by the load cell and a dial gauge respectively .

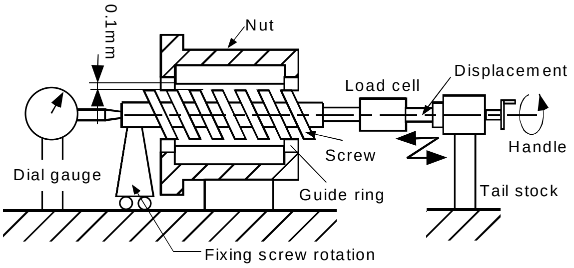


**FIGURE 8**: Axial transmitting load measurement

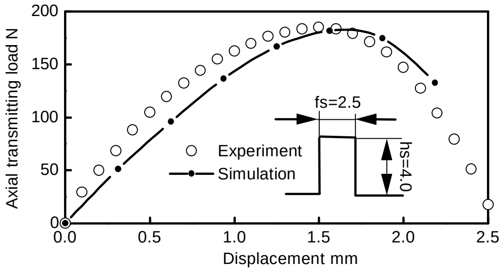
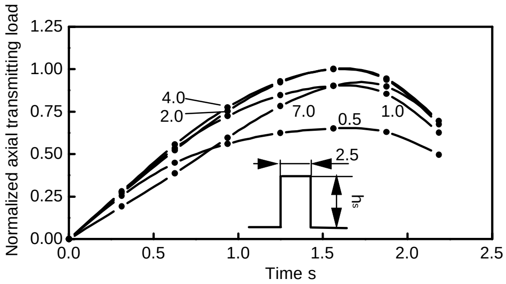
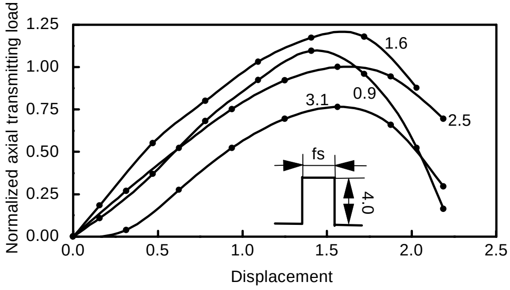


**FIGURE 9**: Axial transmitting load of the prototype MLSM (Experiment and simulation)



(a) Thread depth



(b) Flat width

**FIGURE 10**: Searching for optimal profile (Simulation)

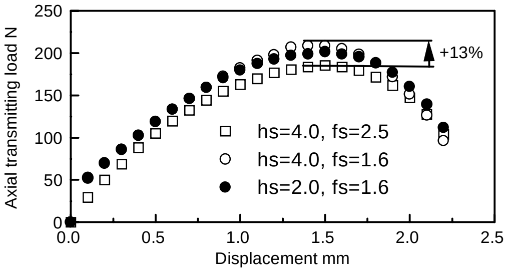


**FIGURE 11**: Measured axial transmitting load of improved MLSMs (Experiment)

Figure 9 shows experimental and simulated axial transmitting loads. For the simulation, the coercive force identified in the previous section is used. The experimental axial transmitting load agrees well with the simulated one, which proves that the FEM model is appropriate for precisely estimating the axial transmitting load . It is considered that a slight difference between calculated and experimental curves could be caused by the friction of the guide rings. At the displacement of 30% of the screw pitch, the axial transmitting load reaches the maximum, and after that, the transmitting load decreases with the increase of the displacement. The maximum transmitting load is about 180 N. The stiffness for 0 to 0.3 mm displacement is 2.3x$10^5$ N/m.

### Improvement of MLSM Profile

To find out an optimal flat width and a thread depth of the screw as shown in Table 1, the axial transmitting loads are simulated, changing the thread depth from 0.5 mm to 7 mm and the flat width from 0.9mm to 3.1mm. The results normalized by the maximum transmitting load simulated using the profiles in Table 1 are shown in Figure 10. Figure 10 (a) shows that the thread depth less than 1 mm or more than 7 mm decrease the axial transmitting load. The reasons for the decreases are; (1) the smaller thread depth induces flux leakage from the bottom of the teeth to the nut, (2) the larger depth decreases the root diameter of the screw so that the magnetic resistance in the screw axis becomes larger which disturbs the magnetic flux flow. Figure 10(b) shows the 1.6 mm flat width has the maximum transmitting load which is improved by 20% as compared with the simulated one of the prototype MLSM.

To prove the simulated results, two types of modified screws are made; one has the same profile as the prototype except 1.6mm flat width, and the other except 1.6mm flat width and 2mm thread depth. The experimental results are shown in Figure 11. Decreasing the flat width from 2.5 mm to 1.6mm, the maximum axial transmitting load increases by 13% as compared with the experimental one of the prototype MLSM. Moreover, the decrease of the thread depth from 4mm to 2mm does not effect the axial transmitting load.

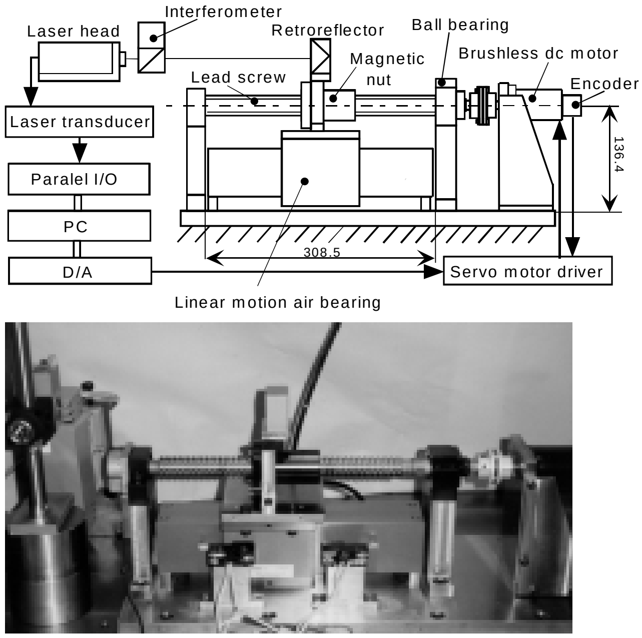


**FIGURE 12**: Experimental setup of positioning system

## POSITIONING SYSTEM USING MLSM

### Experimental Setup

In order to evaluate the performance of the MLSM as a machine element, a linear positioning system that consists of the MLSM, a linear motion air guide and a brushless DC motor (nominal power 100W, maximum torque 0.96 Nm) is introduced as shown in Figure 12. The screw with 2.0 mm thread depth and 1.6 mm flat width is used. The positioning mechanism is free from friction except those of ball bearings supporting the lead screw and the rotor of the brushless DC motor. The total mass of the moving parts including the table of the linear motion air guide, the MLSM nut and a retroreflector as a part of a displacement sensor is 3.34 kg.

The digital state feedback positioning controller with an error integral component is designed using the optimal control method and implemented in a PC, and a laser measurement system (HP5527B, 9.89 nm resolution) as a displacement sensor is applied to the control system . The sampling rate of the digital controller is 0.2 ms. The brushless DC motor is driven by a servo motor driver which requires velocity reference as an input signal.

### Positioning Characteristics

As is shown in Figure 13, an positioning experiment of 0.1 mm and 1.0 mm step responses is carried out. Stable step responses without out-of-step and steady-state errors are achieved. Figure 14 shows stepwise positioning with 0.5 µm resolution. The positioning object vibrates at 40 Hz which is equal to the natural frequency of a mass- spring system where the spring and the mass are respectively the stiffness of the MLSM and the total mass of the positioned object.

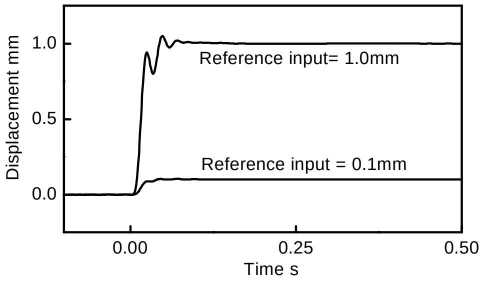


**FIGURE 13**: 1.0mm and 0.1mm step responses (Experiment)

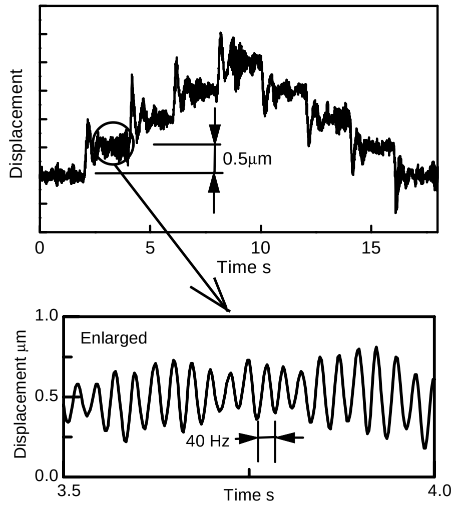


**FIGURE 14**: Positioning resolution (Experiment)

The 0.5 µm positioning resolution is not sufficient to be compared with the displacement sensor resolution (10nm). One of considered reasons for the insufficient positioning resolution is that the low resolution ( 0.6 rpm) of the rotary encoder for velocity control of the servomotor restricts the smooth motion of the screw. It is possible to improve the accuracy of the positioning system by using a rotary encoder with a higher resolution.

### Disturbance Characteristics

Figure 15 shows the experimental setup for disturbing test. The disturbing force is applied to the nut by an electrodynamic shaker and is measured by a load cell . Figure 16 shows experimental compliance ( $X/ F_d$) from measured

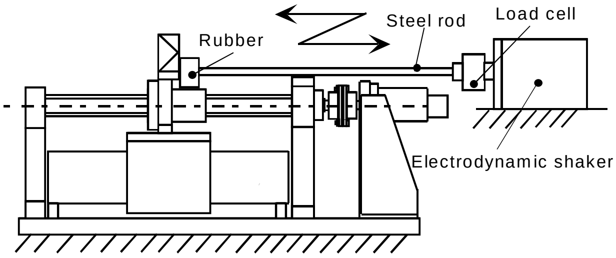


**FIGURE 15**: Disturbing test setup

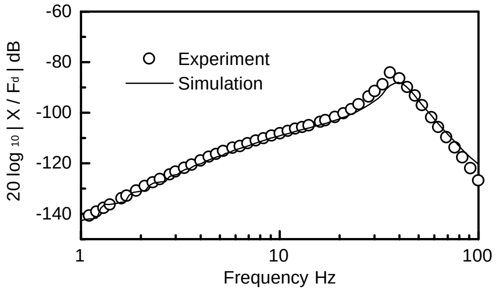


**FIGURE 16**: Compliance characteristics (Experiment and simulation)

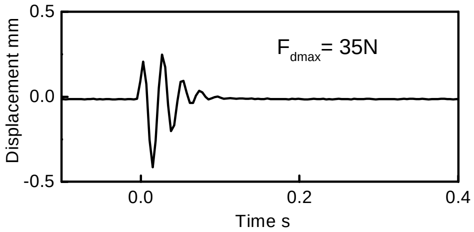


**FIGURE 17**: Impulse force response (Experiment)

displacement (X) and disturbing force ($F_d$) and simulated one by using a dynamic model which is also used to design the state feedback controller. The experimental and simulated ones fit well. Under the state-feedback control, the obtainable stiffness at 1 Hz is about 0.1 µm/N, however, the stiffness decreases to approximate 100 µm/N around 40 Hz . Figure 17 shows the impulse force response. The impulse force (maximum 35 N) generated by the shaker is applied to the nut. The vibration is suppressed within 0.1s.

## CONCLUSIONS

A new type of MLSM which has the helically-magnetized permanent magnetic nut is proposed. Then basic characteristics of the MLSM such as the axial transmitting load and stiffness were measured and optimum profiles were discussed by the simulation and experiment. After that, positioning system using the improved MLSM was made and examined. The following results were obtained.

(1) The maximum axial transmitting load and stiffness of the prototype MLSM having a screw of 25 mm major diameter and 10 mm lead were respectively 180N and $2.3\text{x}10^5$ N/m .

(2) The optimum profile of the screw was found out using the FEM analysis and a 13% increase of the maximum transmitting load compared with that of the first prototype was realized in the experimental MLSM.

(3) 1mm and 0.1 mm stable step responses and 0.5 µm positioning resolution were achieved in the positioning system using the MLSM and the dynamic stiffness at 1 Hz was about 0.1 µm/N.

The stiffness of the MLSM is still 1/100 or less of an ALSM, and is 1/1000 or less of a BLSM of the same diameter as the MLSM. However, the experimental results prove that the MLSM with the appropriate feedback system can work well as the BLSMs and ALSMs.

Furthermore, the other MLSM positioning system consisting of a linear roller guide and a DC motor was constructed and controlled by a nonlinear controller. In the step response test as shown in [4], 10 nm positioning accuracy of the experimental mechanism was verified.

## ACKNOWLEDGMENT

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