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Development and precise positioning control of a thin and compact linear switched reluctance motor

Mohd Nazmin Maslan[a,b], Hikaru Kokumai[a], Kaiji Sato[c,*]

[a] *Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama, Kanagawa 226-8503, Japan*
[b] *Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia*
[c] *Laboratory for Future Interdisciplinary Research of Science and Technology (FIRST), Institute of Innovative Research (IIR), Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama, Kanagawa 226-8503, Japan*

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ABSTRACT

This paper describes the development and precise positioning control of a thin and compact linear switched reluctance motor (LSRM). The LSRM that has been developed has a mover that is easy to fabricate and can be disposable. The mover can be easily separated from the stator, allowing it to be changed frequently or discarded in a hazardous application. The prototyped LSRM mover is only 0.128 mm thick with the stator measuring 2.0 mm at its thickest point. These features are highly desirable for space savings while being cost-effective. However, the LSRM has a strong nonlinear driving characteristic that presents a challenge with respect to precision control. In order to overcome this problem and achieve precision positioning, a linearizer unit was designed and integrated into the controller to compensate for the nonlinear relationships among the effective thrust force, mover position, and excitation current. The usefulness of the designed controller was examined experimentally. The experimental positioning results show that the steady-state errors were all less than 1 μm in the working range of the LSRM. In addition, the redesign for the improvement of thrust characteristic and easy fabrication of the LSRM is explained.

1. Introduction

The switched reluctance motor (SRM) has generated considerable recent research interest due to the advancement of power electronics, digital signal processing, and numerical computing [1]. Further, advanced finite element software now provides a better understanding of the operation and optimum design of the motor. An SRM is a type of electric motor in which the rotor tends to move to a position where the inductance of the excited winding is maximized or the reluctance is minimized and can be of a rotary or linear design [2]. The torque or force generation involves the switching of phase current depending on the rotor position. Many studies have been published covering the technical aspects of modeling, design, and control for rotary SRMs [3]. There remains, however, a need for further study of the linear counterpart. Various structures of linear switched reluctance motors (LSRMs) have been developed over the past few decades [1,4–7].

Linear drive mechanisms such as LSRMs have increasingly been being considered as they can reduce the reliance on rotary-to-linear motion converters. A thin and compact motor would be beneficial for space savings. Moreover, LSRMs have no rare-earth permanent magnets that are widely used in high-speed linear motion mechanisms. This characteristic could reduce the manufacturing cost and environmental problems related to recycling. In addition, having movers that are completely independent from the stator will open up new markets for disposable movers in hazardous environments that previous research did not consider [1,5,7].

To increase the diversity of applications, it is important to establish a precision positioning method for these motors. However, LSRMs have strong nonlinear driving characteristics [8]. The results on precision positioning have been reported in [1] where they achieved promising results by including a novel current–force–position lookup table and a plug-in robust compensator in the controller. The positioning in long and short working ranges was accomplished with maximum steady-state error of

* Corresponding author.
E-mail address: sato.k.ah@m.titech.ac.jp (K. Sato).

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3.5 μm. Although the position response for short working ranges was unsatisfactory, the concept of using the lookup table to perform the force linearization will be valuable to this study. In [9], their control system also included a lookup table for the force compensation. For point-to-point repeatability, positioning errors of 5 μm were achieved.

An adaptive controller that observes and regulates the modeling of the LSRM was applied in [10]. The positioning errors were not given. An adaptive position control method based on online parameter identification and a pole-placement regulation scheme was designed in [11]. Static error up to 2.5 μm occurred with a step height of 20 mm. In [12], the operating performance of fuzzy PID and conventional PID controllers was compared using simulation. Systems using adaptive controllers [10,11], or an intelligent controller [12] require much knowledge of control techniques. A controller that is easy to design and adjust is desired to increase its usability.

This paper describes efforts to improve the thrust characteristic of a thin and compact LSRM previously developed [13] as well as precision positioning of the LSRM. The LSRM has been redesigned to reduce its magnetic resistance resulting in a higher thrust force characteristic than in previous work. This redesign resulted in a thinner mover and a simpler fabrication process, making it both easier to disassemble and highly recyclable. We also attempted to design a controller for precision positioning with the developed LSRM. Although the average thrust of the developed LSRM is higher than the previous one, the LSRMs show significant nonlinear thrust characteristics. In order to overcome the nonlinearity problem, a suitable linearizer unit was constructed to suppress the nonlinear characteristics including the friction effect. For the linearizer unit design, a dynamic model of the LSRM was developed and the relationships among the calculated effective thrust force, mover position, and excitation current were validated. The point-to-point positioning performance with the proposed controller was examined. According to [14], the level for precision positioning awareness, approximately 1 μm, has not been achieved in previous research. The proposed controller is able to achieve this level of precision while retaining the ease of design and adjustment.

The remainder of this paper is organized as follows. Section 2 explains the motor structure and the driving principle of the LSRM. Section 3 describes the improvement in the mover structure and its fabrication process. The prototype of the experimental setup along with its basic driving characteristics is also covered in this section. Section 4 explains the dynamic model developed for simulating the nonlinear driving characteristics. In Section 5, the positioning results and the problem associated with the conventional PID are described. Then, the proposed controller design including the linearizer unit is described and the positioning performance of the control system is examined. Finally, Section 6 presents the conclusions of the present study.

2. Motor structure and driving principle

2.1. Motor structure

The developed LSRM has three distinctive features: (1) both the stator and the mover are thin; (2) an absence of permanent magnets; and (3) a simple mover completely independent from the stator. Fig. 1 illustrates the basic structure of the LSRM. The LSRM consists of an active stator and a passive mover. The stator has rows of slots and core teeth; coils are wound around the core teeth. Twelve coils are divided into three-phase coils where the corresponding phases are connected in series opposing each other along the traveling direction.

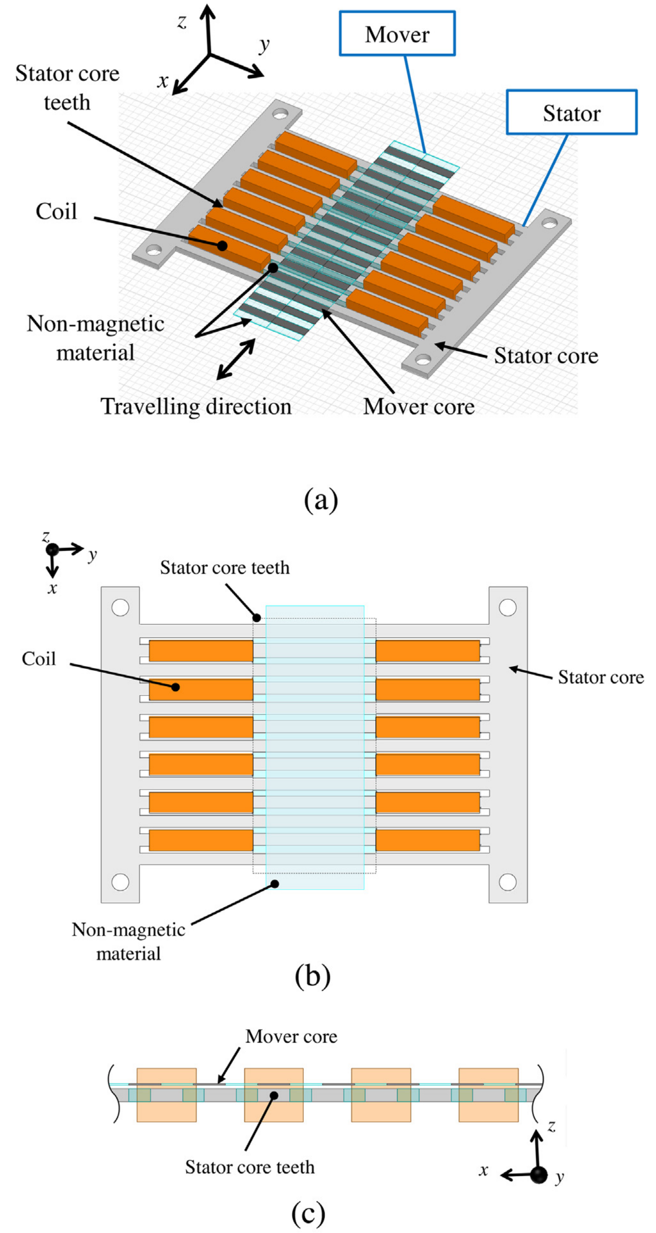

Fig. 1. Basic structure of the LSRM (a) 3-D view (b) Top view of stator (b) Cross-sectional view.

Meanwhile, the mover lays flat on the stator surface between the coils. The simple mover is made up of mover cores wrapped around two different non-magnetic films, one that has adhesion properties while the other has low-friction properties. It is easy to fabricate and can be disposable. When not in operation, the mover can be separated effortlessly from the stator allowing it to be changed frequently and discarded in hazardous applications.

2.2. Driving principle

Fig. 2 shows magnetic circuit AA', one of several magnetic circuits. As shown in the figure, when current is applied to phase AA' coils, magnetic flux is generated from both ends of the coils facing each other. The flux flows straight to the mover core at the center and returns back to perform a cycle. To reduce the reluctance or magnetic resistance, the mover cores near the active phase coils are pulled toward the stator poles on the left (positive x direction).

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