ROBUST CONTROL FOR PRECISION MOTION OF A THIN AND COMPACT LINEAR SWITCHED RELUCTANCE MOTOR

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ABSTRACT: This study presents the robustness of the precision motion control system of a thin and compact linear switch reluctance motor (LSRM). The control system employs a linearizer unit along with a feed forward element and a disturbance observer for precision motion performance. Although numerous tracking experiments were carried out to evaluate the effectiveness, their robustness towards sudden load and speed change remains unclear. We performed a sudden load of 50% change in mass and a sudden speed variation 4 times as fast as initially. By conducting the experiments, we found that it takes approximately 0.05 s for the control system to regulate to the determined ramp-reference motion, and the precision motion performance was maintained having a maximum absolute tracking error of less than 5 μm. In conclusion, these results indicate that the control system has the ability to quickly suppress the sudden load and speed change.

KEYWORDS: *Linear Switched Reluctance Motor; Thin; Disposable Mover; Robust Control; Precision Motion*

1.0 INTRODUCTION

Linear drive mechanisms such as electromagnetic linear motors are suitable driving units for a high-speed and high-precision system [1-2]. However, permanent magnets (PMs) used in the motors have powerful attractive forces. To avoid the usage of PMs, a linear motor based on a linear switched reluctance motor (LSRM) can be considered, making it easy to assemble and disassemble it. Without the bulky PMs, the basic structure of the LSRM is thin and compact. Achieving precision control is, however, difficult due to the three-dimensional relationship among the thrust force, applied current, and mover position [3]. In addition, the motor exhibits a nonlinear friction that further reduces the effective thrust force, which changes with respect to the applied current and mover position.

The demand on high-precision performance has increased [4-5]. The study by Gan et al. [6] is one of the earliest studies on precision performance. They proposed a concept that helps employ a novel current–force–position lookup table to linearize the force, which has been valuable to this study. Although numerous studies on the applications of LSRMs pertaining to precision positioning have been reported [7-10], only a few tried to achieve precision motion performance. Zhao et al. [11] designed a robust passivity-based control algorithm based on the dissipated energy. Although they claimed that the trajectory-tracking performance using the proposed algorithm was excellent, the tracking errors were never provided. Chen and Li [12] employed a trajectory-tracking technique based on iterative control and hybrid iterative learning control methods. The tracking errors were reduced to an average value of 0.7 mm for a sinusoidal reference of amplitude 5 mm. A decoupling-motion control algorithm based on torque and force distribution functions was used to obtain a better operational performance, without providing the tracking errors [13]. In addition, other than the aforementioned LSRM, studies on precision motion performance of planar switched reluctance motor have been reported. The maximum absolute tracking errors using a nonlinear cascade controller for the planar motors [14] and the modified planar motors [15] were 0.5 mm and 22 μm, respectively.

This paper presents robust control for precision motion performance of the developed LSRM based on the precision motion control system in [16]. Although numerous tracking experiments were carried out previously [16], their robustness towards sudden load and speed change remains unclear. As the robustness of the control system is critical, the sudden load and speed change on the motion performance were investigated experimentally.

The remainder of this paper is organized as follows. In Section 2, the prototype as well as the structure of the precision motion control system are explained. Section 3 describes the tracking results and discussion are described. Finally, Section 4 presents the conclusions of this study.

2.0 METHODOLOGY

2.1 Prototype of the LSRM

Figure 1 shows the schematic diagram of the experimental setup. A digital signal processing (DSP) system provided the driving signals to be applied to the commercial current amplifiers. These amplifiers are used to drive each phase of the coil. Simultaneously, the DSP system obtains the displacement of the mover from the linear encoder.

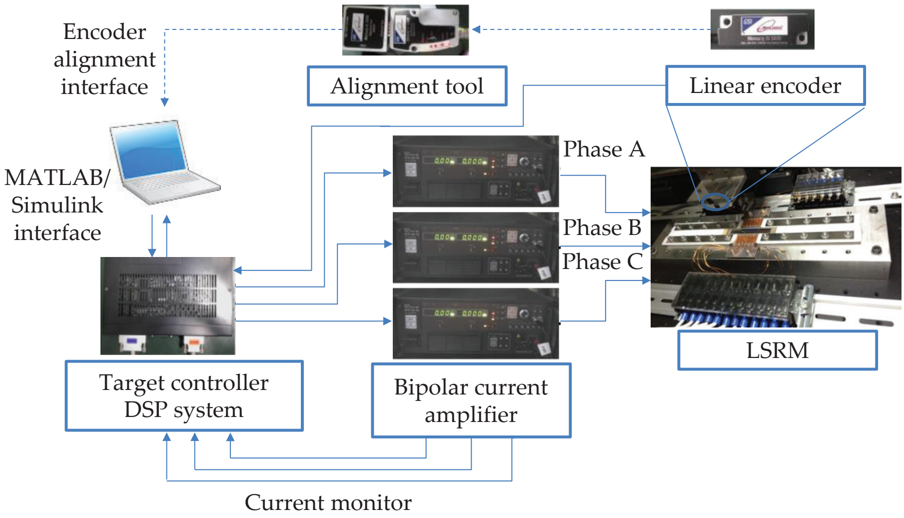
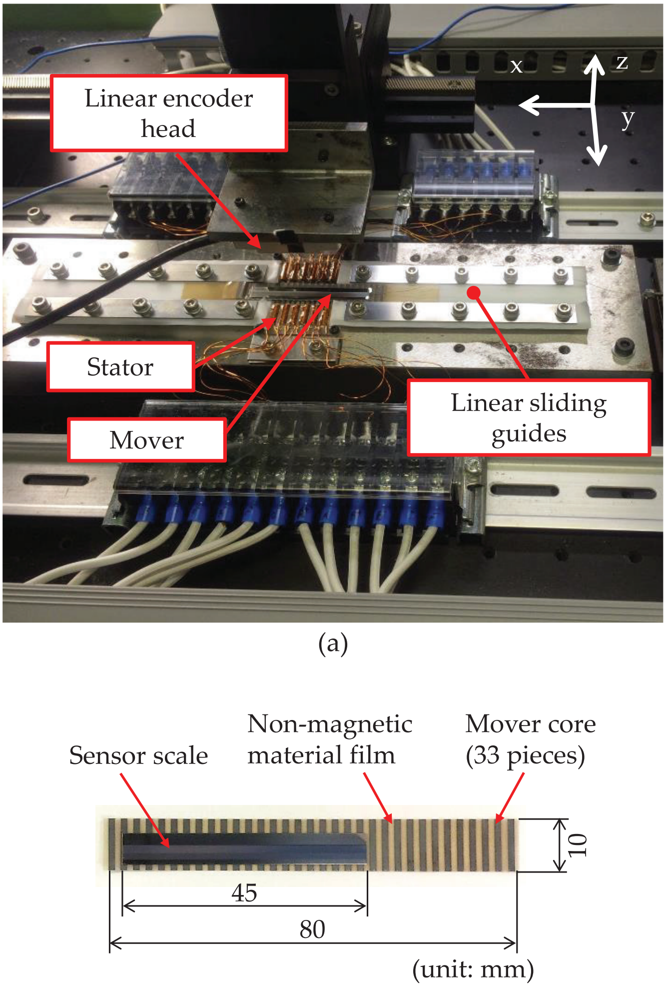


Figure 1: Schematic diagram of the experimental setup

Figure 2(a) shows the overall view of the prototype LSRM, while Figure 2(b) shows the fabricated mover. The mover has a length of 80 mm and a total weight of 0.67 g, a 20% change in mass over the ones used in [7]. It is placed on the sliding surface between the stator coils. The surface is bonded with a low-friction polytetrafluoroethylene (PTFE) film, supported by a PTFE linear sliding guide The displacement of the mover is obtained using a linear encoder (Mercury II 5800 by GSI Group Inc.) mounted above the motor.



(a)

(b)

Figure 2: Overall view of (a) prototype LSRM and (b) fabricated mover

2.2 Structure of the Precision Motion Control System

Figure 3 shows the block diagram of the control system for precision motion. The linearizer unit was constructed in [7] to suppress the high nonlinearity of the driving characteristics. It includes a feed forward (FF) element and a disturbance observer to compensate the dynamic characteristic and to reduce the negative influence of the unknown disturbance force [17]. They were designed using the same procedure and has the same parameters as in [16].

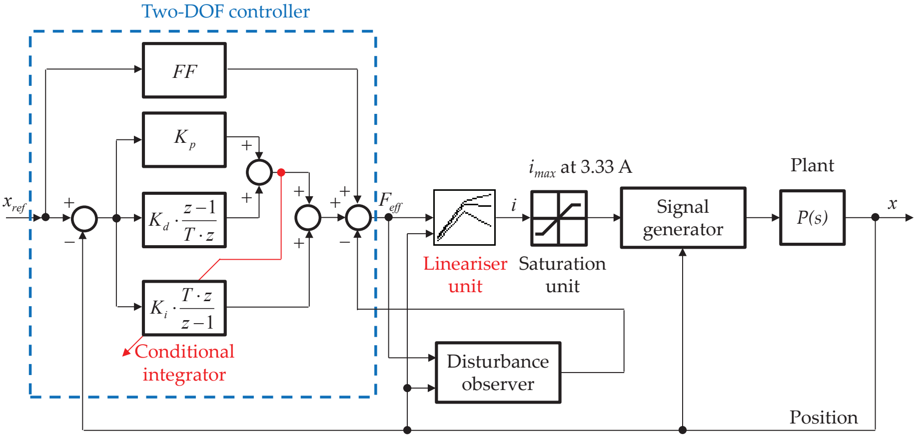


Figure 3: Block diagram of the control system for precision motion

3.0 RESULTS AND DISCUSSION

Tracking experiments were conducted to evaluate the effectiveness of the control system described in Section 2.2. Table 1 lists the determined gains used for the PID element. The gains were determined experimentally and adjusted to reduce the steady-state error during positioning [7]. The control sampling frequency was 10 kHz, and the linear encoder's resolution was set to 0.1 μm.

Table 1: Control parameters

Symbol	Description	Value (unit)
K_p	Proportional gain	20 (N/m)
K_i	Integrator gain	60 (N/m)
K_d	Derivative gain	0.3 (N/m)

Figure 4 shows the ramp response of the control system for precision motion at input 3.75 mm/s. The maximum absolute tracking error is approximately 2.8 μm. At positions where the phases are switched, a high rate of change of current induces vibrations, however, errors were reduced sufficiently using the control system. Previous works in [16] had shown that even when there is a change on the length and mass of the movers, the same precision motion performance is achieved with maximum absolute tracking errors within 5 μm.

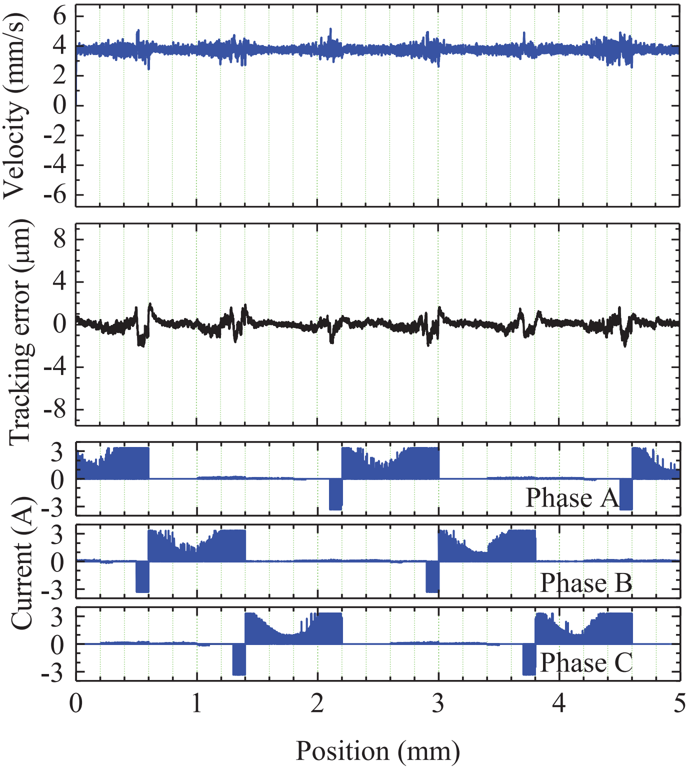


Figure 4: Ramp response of the control system for precision motion with respect to position

In order to verify the robustness of the control system to the sudden load change, a load with a 50% change in mass was dropped at 0.35 s, shown in Figure 5. The mover in Figure 2(b) was used as it has an area exposed for the load to be dropped. The load is made from 0.3 mm thick copper plate. As can be seen, it takes approximately 0.05 s for the control system to regulate to the determined ramp-reference motion.

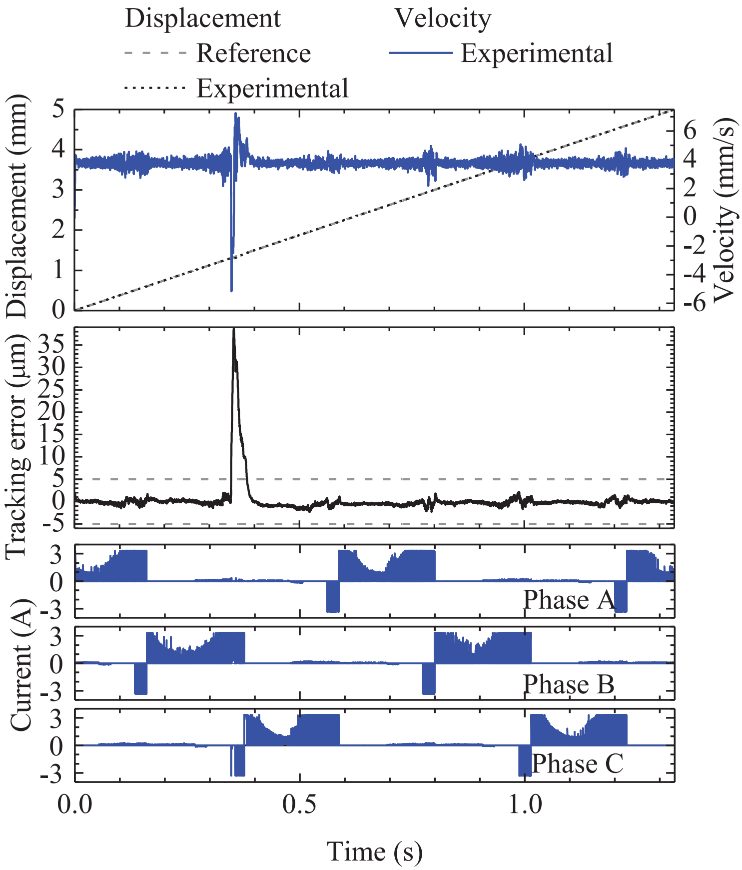


Figure 5: Tracking response of the designed control system under the influences of the sudden load change with ramp response: 3.75 mm/s with respect to time

On the other hand, Figure 6 shows the robustness result of the control system to the sudden speed change, whereby a sudden speed variation 4 times as fast as initially were carried out at 1 s. Again, it takes approximately 0.05 s for the control system to regulate to the determined ramp-reference motion and the precision motion performance was maintained. These experimental results indicate that the control system has the ability to quickly suppress the sudden load and speed change.

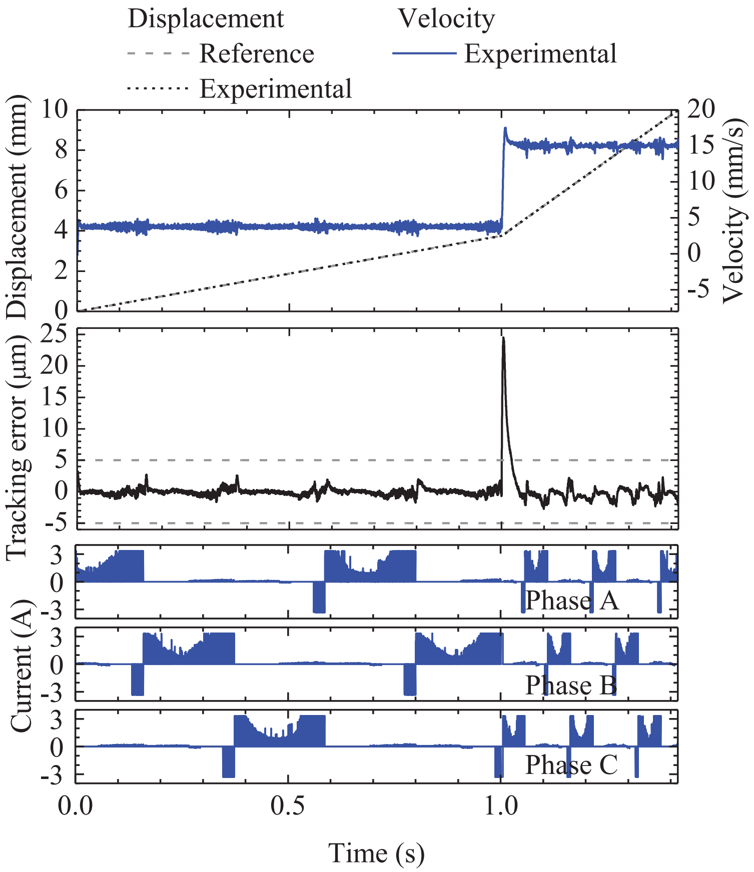


Figure 6: Tracking response of the designed control system under the influences of the sudden speed change with ramp response: from 3.75 to 15 mm/s with respect to time

4.0 CONCLUSION

In this paper, the robustness of the precision motion control system of a thin and compact LSRM was presented. As the robustness of the control system is critical, the sudden load and speed change on the motion performance were investigated experimentally. By conducting the tracking experiments, we found that it takes approximately 0.05 s for the control system to regulate to the determined ramp-reference motion and the precision motion performance was maintained. The experimental results indicate that the precision motion control system has high robustness to the sudden load and speed change.

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