Design of a Linear Switched Reluctance Motor for High Precision Applications

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Abstract— **This paper describes the design of a linear switched reluctance motor (LSRM) for high-speed high-precision point-to-point motions. An S-shaped curve is first chosen as the trajectory motion profile and then a simple yet effective design procedure is introduced to design the motor's mechanical dimensions. Theoretical deduction and experimental results on the phase inductance and the static force generation are presented and compared with each other. The final design has a simple and robust structure. Measurements from the fabricated LSRM show that the motor has met all design specifications. The resultant LSRM is very useful in high-precision applications, especially in semiconductor fabrication machineries.**

I. Introduction

Switched reluctance motor has never been a popular choice for high-precision and high-speed motion actuator; because it is difficult to control and its output has high torque ripples. This is due to the fact that the actuator's characteristic is highly dependent on its complex magnetic circuit, which is difficult to model, simulate, and control. There is little in recent literature which concerns with high performance motion control of switched reluctance linear drive systems. It was only until recent years which we see a general surge of interest in the switched reluctance motor [1]. This was mostly due to the advancement of power electronics and digital signal processing, and the continuous trend of "simplifying the mechanics through advance control strategy".

The purpose of this project is to develop a novel, high performance, direct drive, and linear motion actuator system for precision position control applications. The actuator is based on switched reluctance technology [2]. The linear direct-drive actuator has a simple and robust structure with low inertia and direct drive capability, and it is particularly suitable for high-precision and high-speed manufacturing machinery. Manufacturing of the LSRM is simple, and it is very suitable for high-precision travel over long distances. Unlike other types of motion actuators, mechanical couplings, lead screws, magnets, and brushes are not required in LSRM [3]. Special mechanical adjustments or alignments are also not necessary. Comparing to permanent magnet linear motor, the proposed actuator has a much simpler structure and is less expensive. It is also more robust and more fault tolerant, and has less overheating problem.

II. Design Specifications

All mechanical system has a limited control bandwidth; its step response always exhibits overshoots or oscillations. In order to avoid the undesired oscillatory response, a third order position S-profile with limited input bandwidth is used, so that the output position can track the reference command accurately. Equation (1) governs the 3rd order S-profile generation:

$$\begin{aligned} \frac{da}{dt} &= \{J_{max}, 0, -J_{max}\} \\ v &= \int a dt \\ s &= \int v dt \end{aligned} \tag{1}$$

where a , v and s are the acceleration/deceleration, velocity and position of the S-profile respectively while J_{max} is a pre-set jerk constant. Figure 1 shows the typical position, velocity, and acceleration profiles of an S-shaped trajectory profile. The profile has a maximum acceleration/deceleration of $A_{max} = 2.5$g and a maximum velocity of $V_{max} = 1\text{ms}^{-1}$. The LSRM is designed to track the above type of S-shaped position profile, with the specifications listed in Table I.

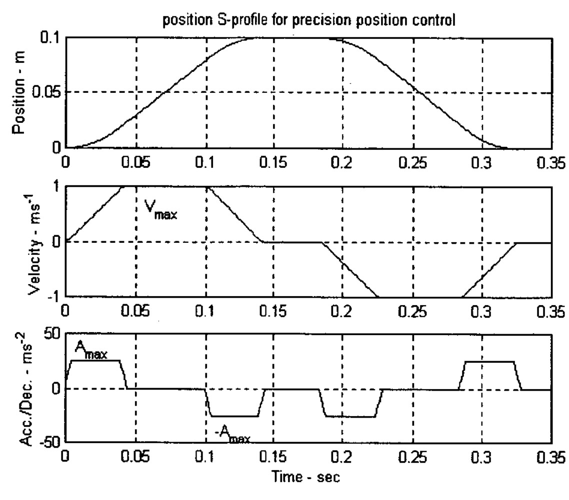

Fig. 1. A third order position S-profile.

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TABLE I

MOTOR SPECIFICATIONS.

Max loading	4.6kg
Max acceleration/deceleration	2.5g
Max velocity	1ms^{-1}
Max travel distance	300mm
Position accuracy	$\pm 25\mu m$

III. CONFIGURATION OF THE LSRM

The first step in the LSRM design is to choose a basic magnetic path configuration [4]. A three phase flux de-coupled motor windings with longitudinal configuration is chosen because of the following advantages:

- The de-coupled flux windings lead to a simpler motor model due to zero mutual inductance [6].
- The individual phase windings reduce the manufacturing cost and complexity.
- Long travel distance can be accomplished easily by combining longitudinal track guides.

Figure 2 shows the design schematic of the LSRM. The motor is integrated on a precision linear motion guide. The track guide and the core of the windings are laminated with 0.5mm silicon-steel plates. A $0.5\mu m$ resolution linear optical encoder is mounted on the motion actuator to observe the motion profile and provides the position feedback. Figure 3 shows the three-phase coil arrangement with flux de-coupled path and 120 electrical degree separation.

IV. DESIGN OF THE LSRM

After choosing the motor configuration, then next step is to design the motor's mechanical dimensions so that the design specifications listed in Section I can be fulfilled. In our application, the maximum loading is 4.6kg and the maximum acceleration is 2.5g; therefore the maximum force F_{max} developed in each phase should be equal to or grater than 115N.

With the dimension symbols defined in Figure 3, the force generation equation in linear region of each phase is equal to [5]:

$$f_e(x,i) = -\frac{\pi}{y_2} i^2 L_\Delta \sin\left(\frac{2\pi x}{y_2}\right) \tag{2}$$

where x is the travel distance, y_2 is the pole pitch, i is the phase current and $2L_\Delta$ is the change of phase inductance from aligned to unaligned position.

The dimensions y_1 and y_2 are fixed to be 5mm and 10mm respectively as there is a standard press tool in our laboratory for these particular dimensions. Furthermore, the maximum motor driver phase current i_{max} is equal to 10A; therefore, in order to generate $F_{max} \geq 115$N , we need

$$115 \leq \frac{\pi}{10^{-3}} 10^2 L_\Delta \Rightarrow L_\Delta \geq 3.661\text{mH}.$$

In general, L_Δ is a function of the motor geometry (y_1, y_2, l, z) and the number of turns of the motor winding, N. The phase inductance can be represented by a Fourier series. If the first order approximation assumption is made, the phase self inductance is equal to [6]:

$$\begin{aligned} L(x) &= L_{ls} + L_0 + L_\Delta \cos\left(\frac{2\pi x}{y_2}\right) \\ L_0 &= N^2 \mu_0 l N_s C_0 \\ L_\Delta &= N^2 \mu_0 l N_s C_1 \end{aligned} \tag{3}$$

where L_{ls} is the phase leakage inductance and N_s is the number of teeth on a primary side pole. Note that there is no mutual inductance between phases because of the novel flux de-coupled winding arrangement. The Fourier coefficients C_0 and C_1 for the normalized permeance of one teeth can be found in [7]. In our design project, N_s is equal to 2, l is chosen to be 25mm and z is chosen to be 0.5mm

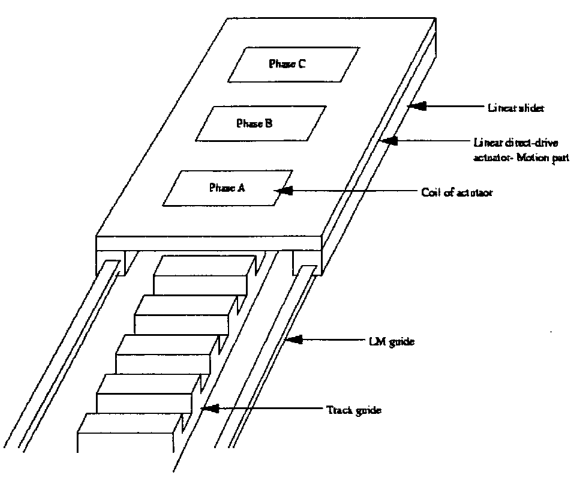

Fig. 2. Schematic of the LSRM.

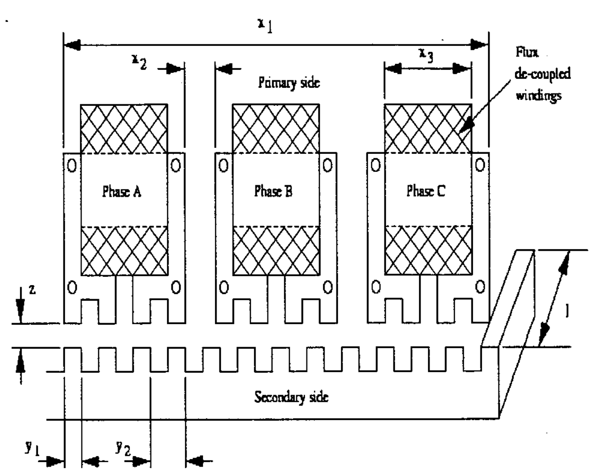

Fig. 3. Three-phase flux de-coupled motor windings.

for an easy mechanical alignment, then the values of C_0 and C_1 can be found from [7] and the numerical figures are listed in Table II.

TABLE II
PHASE INDUCTANCE COEFFICIENTS.

	$(y2-y1)/y1=1$
$y_2/z=20$	$C_0=9.363, C_1=2.524$

If L_Δ =4mH is set to satisfy the maximum force requirement and guarantee a proper safety margin, then from Equation (3), N =159 turns, L_0 =14.87mH and F_{max} =125.7N are evaluated. Finally, the mechanical dimensions of the proposed LSRM are summarized in Table III. The proposed LSRM is fabricated according to the designed parameters and the photo of the LSRM prototype is shown in Figure 4.

TABLE III
MOTOR MECHANICAL DIMENSIONS.

Pole width (y_1)	5mm
Pole pitch (y_2)	10mm
Motor length (x_1)	121.666mm
Phase separation (x_2)	8.333mm
Winding length (x_3)	15mm
Winding width (l)	25mm
Air gap width (z)	0.5mm
Number of turns per phase (N)	159

V. Experimental Verification

Two experiments are performed to validate the design parameters. The first experiment is to measure the phase inductance against travel distance and the second one is to measure the static force against travel distance by a load cell and a mechanical test-rig. Figure 5 shows the comparison between simulation and experimental results. The upper part of Figure 5 shows the phase inductance variation, the average value of the experimental data is almost 0.8mH higher than the simulation result, this is mainly due to the leakage inductance and the laminated core inductance. The change of inductance from aligned to unaligned position is very close to the designed value.

The lower part of Figure 5 shows the static force comparison, it was found that the simulation result and the experimental measurement of static force matches very well (<5%) when the current is below 8A. However, saturation effect in the force generation is found when the phase current is over 8A, it is not surprising as this observation is the well-known saturation characteristic in switched reluctance motor. This also explains why a safety margin is added in Section IV to account for the saturation effect. Finally, the measured maximum force is around 115N when the phase current is equal to 10A, which can fulfill our design specifications.

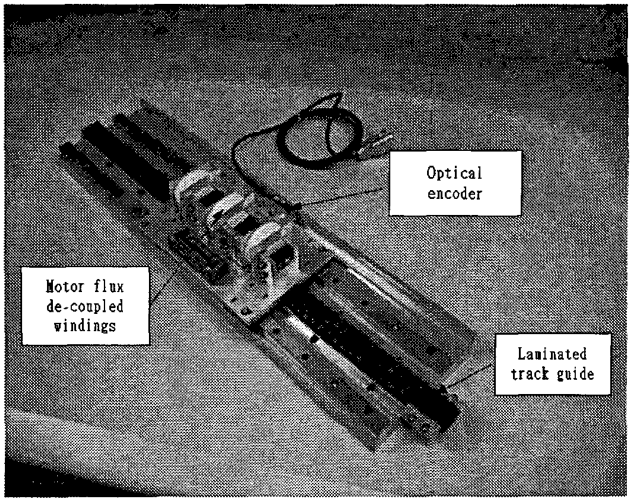

Fig. 4. Photo of the LSRM prototype.

VI. Conclusions

In this paper, a LSRM for precision position control application is designed, manufactured and verified. Furthermore, a simple yet systematic LSRM design procedure is introduced. The design is based on an effective S shaped trajectory profile.

The experimental and simulation results match quite well when the phase current is less than 8A. Thus the result validates the design methodology. A further experiment will be performed and a 3-D force-current-position model that includes saturation characteristics will be developed shortly.

In conclusion, the LSRM described in this paper is robust, reliable and has little mechanical adjustments. Due to its performance and low manufacturing cost, the actuator can be applied to many new and high-end applications

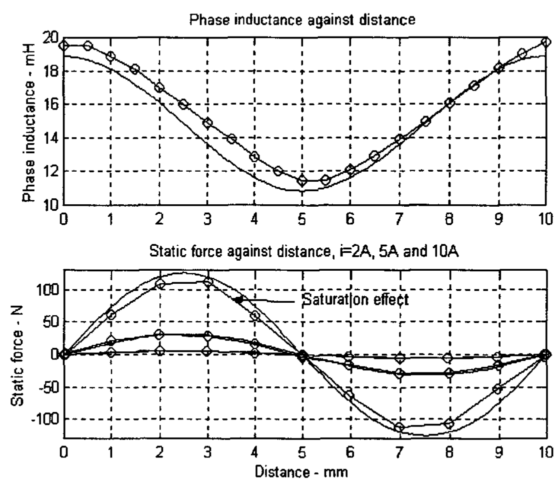

Fig. 5. Experimental verification. Solid line — simulation results, o — measurement results.

which require high-precision and high-speed motions. It will also have a tendency to replace many traditional X-Y *tables that* operate by rotary motors and mechanical lead screws.

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