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Design and analysis of a DSP-based Linear Switched Reluctance Motor

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Abstract—In this paper, an "active-mover-passive-stator" structure of linear switched reluctance motor (LSRM) is proposed with DSP control implementation. The motor has the characteristics of simple and robust mechanical structure. The design improvement is discussed and further verified with finite element analysis (FEA). The DSP-based position control scheme is implemented and experimental results prove the effectiveness of control design method.

Keywords-Linear switched reluctance motor, FEA, DSP

I. INTRODUCTION

In modern manufacturing industry, linear motion systems that are capable of high precision and high speed are especially required. Currently linear motion is achieved mostly by the combination of rotary motor and mechanical translators such as gears and belts. The actuator based on such components commonly has a complex mechanical structure, high system cost and it often requires constant maintenance. Due to the backlash and wear from the mechanical components, the accuracy and stability of the overall motion system may be affected.

In a direct-drive system, the mechanical output is directly coupled to the actuator and load. Therefore it has the characteristics of high force density, high efficiency and low production cost [1]. By elimination of mechanical couplers that transforms rotary motion to linear one, the actuator can be designed with the integration of the control object and load. Therefore the control system has the characteristics of fast response, high flexibility and an overall simplified structure. Currently the linear direct-drive system based on permanent magnetic motor principle is available to industry. Since this type of linear motor requires rare-earth permanent magnets to facilitate magnetic path and force output, the control system has high production cost and a complex structure. Due to the demagnetization effect of permanent magnets, this kind of linear motion system is limited for further popularization in industry.

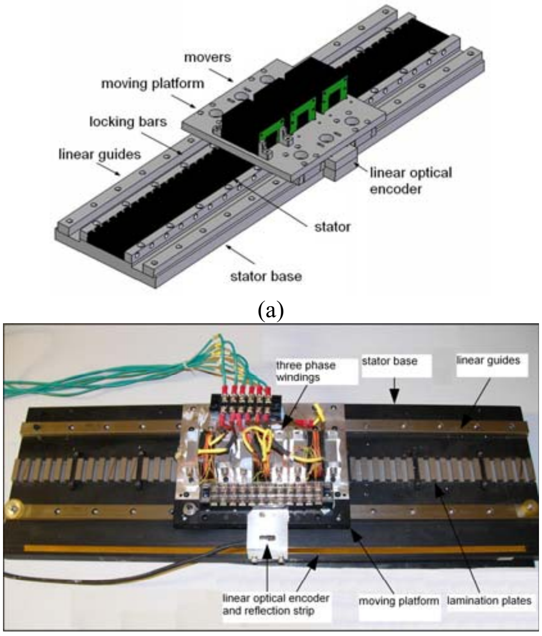
Compared with a linear permanent magnet motor (LPMM), a linear switched reluctance motor (LSRM) is mechanically stable with no expensive materials involved. The overall construction cost is comparatively low to that of a LPMM. However, the control algorithm is more complicated since linearization scheme and specialized control algorithm maybe required due to the nonlinear characteristics of a LSRM.

II. DESIGN IMPROVEMENT OF THE LSRM

The overall motor structure is shown in Fig.1. The linear motor applies the "active-stator-passive-translator" structure for the following reasons [2],

- Simplified winding scheme on the movers
- Flexible arrangement of travel distance
- Convenient manufacture of moving platform and windings

The linear motor is composed of the moving platform and the stator base, which are made of aluminum alloy to reduce overall weigh and volume. A pair of high-grade linear guides is installed on both side of the stator base to facilitate linear movement. The stator is composed of laminated silicon-steel plates with toothed structure. To avoid air gap deformation from large attraction forces, a pair of linear locking bars is employed with long screws to hold the stator plates tightly. In comparison of the previous version [3], orifices through the lamination plates are no longer required which compromise the magnetic path and efficiency. The movers consist of three-phase windings, with each separated 120° electrically. Four L-shaped locking pins are employed with one side fixed to the mover plates and the other screwed on the surface of the moving platform. This structure enables prevention of air gap deformation from large attraction forces. To ensure a large propulsion force output at the same time, the air gap distance between the mover and the stator is fixed as 0.2 mm as shown in Table 1 of mechanical and electrical parameters for the LSRM. Compared with the previously built LSRM model, this design has more mechanically robust structure. Larger propulsion force output is expected with the same current level excitation.



(a)

(b)

Fig. 1: The LSRM (a) overall structure and (b) actual picture

Table1 Mechanical and electrical parameters

Mass of moving platform	2 Kg
Mass of stator base	3.5 Kg
Stroke of moving platform	220 mm
Pole-pitch	12 mm
Tooth width	6 mm
Encoder resolution	0.5 µm
Air gap	0.2 mm

III. CHARACTERIZATION OF THE LSRM

The purpose of motor characterization is to test the mutual inductance between any two phases to determine whether any decoupling mechanism is required for control algorithms. In addition, some mechanical parameters can be obtained from FEA such as attraction and propulsion forces for performance prediction of the motor prototype.

A. Mutual inductance

Any two movers can be selected for the test of mutual inductance as shown in Fig.2. When one mover is excited with direct current such as 8A, flux is established between the active mover, the stator and the air gap in between. By the inspection of flux distribution from the other mover, mutual inductance can be observed. For precise analysis, the cross-section of the LSRM is investigated as shown in Fig.3 that the maximum induced flux value is about 1‰ from the excited value. It can also be concluded that the induced value decreases as the distance between the active and passive mover increases. Therefore the coupling effect between any two movers is negligible.

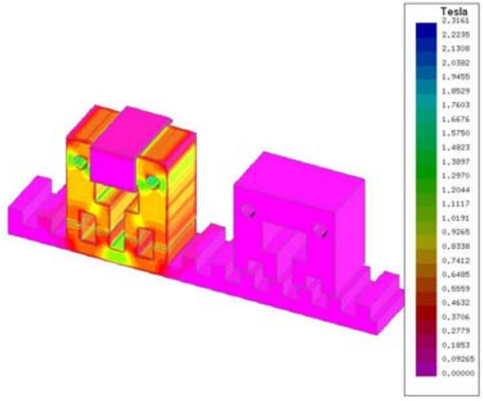
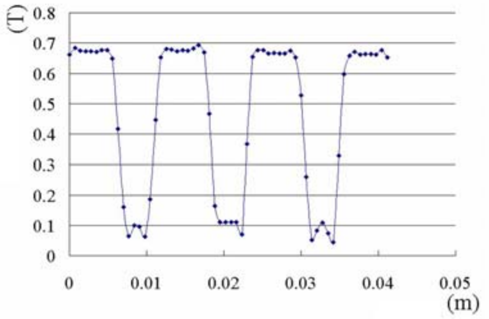
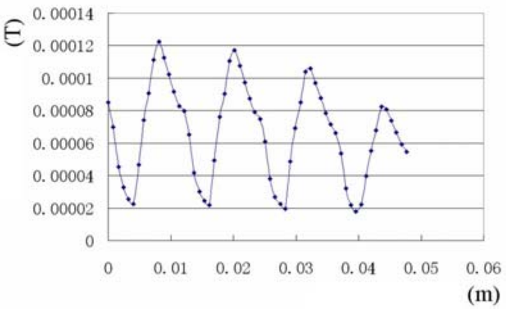


Fig. 2: Magnetic flux distribution



(a)



(b)

Fig. 3: FEA results of mutual inductance

B. Propulsion force

Considering of current excitations according to different relative positions between one mover and stator, the FEA results are shown in Fig.4. Under small amount of current levels less than 8A, force profile is quasi-sinusoidal waveforms and maximum force output occurs at half pole-pitches as 3 mm and 9 mm. This corresponds to the force output performance from a typical SRM under unsaturated condition. As the excitation current increases, maximum force value arrives earlier compared with the one at low current levels. This is because the motor is under operation of saturation with more end and edge effects [4]. Compared with simulation results, the measurement yields less force values at the same current excitation levels due to frictions.

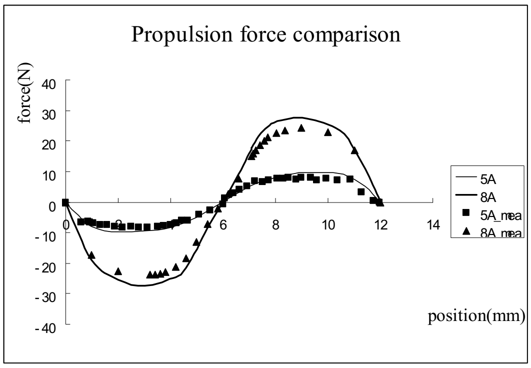


Fig.4 Propulsion force output

IV. CONTROL IMPLEMENTATION WITH DSP

A. Hardware design

The hardware of the linear motion system consists of the control unit (DSP), the position sensor, current detection and protection circuit, display and drive, etc. The overall control structure is shown in Fig.5.

a. Control unit

The control unit applies a single-chip DSP TMS320F2812 from Texas Instruments specialized for motor control [5]. F2812 DSP is a type of 32-bit industrial microprocessor, including flash memory on board and processing speed up to 150MIPS. The DSP chip integrates rapid A/D converter, event management units, quadrature encoder circuits and other interface necessary for control applications. The F2812 chip is capable of real time computation for various complicated control algorithms including regulated PWM signal generation and digital current loop, which is essential to switched reluctance motor with torque ripple reduction.

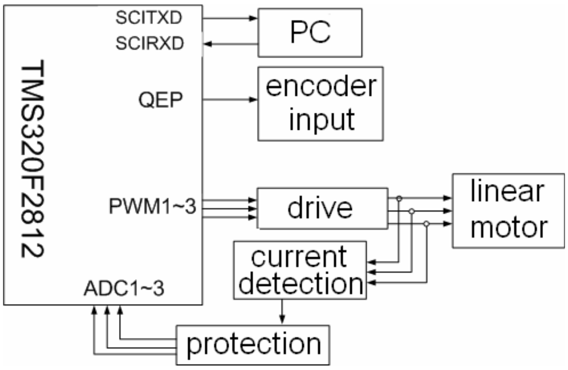


Fig.5 Control diagram of the LSRM

b. Sensor interface

The linear optical encoder with 0.5 um resolution is applied as the feedback component for real time position information detection. The Quadrature Encoder Pulse (QEP) function from the event management unit interfaces the linear encoder and transforms the captured signal into correct position counts. To match voltage level and improve anti-interference capabilities, the pulsed encoder signal is transmitted through opto-couplers with electric isolation.

c. Current detection

Hall-effect devices for real time current detection are employed. The feedback signal is input through A/D converster for implementation of digital current control loop. At the same time, it is transmitted to protection circuit for over-current disconnection of main power switch devices.

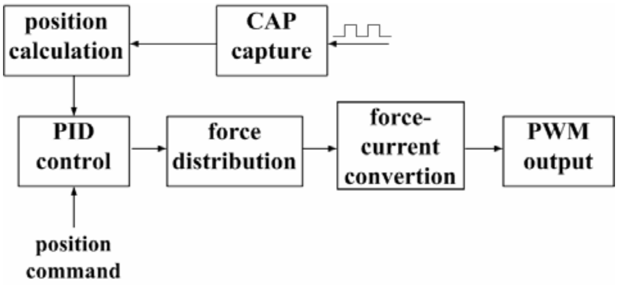


Fig.6 DSP-based signal flow diagram

B. Software design

The task of the main program is to set the system clock, initialize the event manager (CAP unit), the timers, serial and PWM interfaces, and provide position and current display in real time. As shown in Fig.6 for the signal flow diagram, control values for PID are calculated according to the current and feedback position values. The simple multi-excitation scheme [6] is applied to reduce force ripples as the force distribution function and certain phase(s) are excited according to current position information. The linearization of force to current module is implemented for the reference of PWM command.

The first interrupt service program is employed for the calculation of position command to generate square waveforms of amplitude 15 mm, frequency 1 Hz. The second interrupt program generates PWM waveform with a period of 20 us and regulates the duty cycle according to current reference command. Timer3 interrupt program is responsible for accumulation the frequency of overflow to calculate current motor position. Timer4 is applied as the time base for CAP uint and capture the rising/falling edge to judge the movement direction of the motor.

Software flowchart is shown in Fig.7.

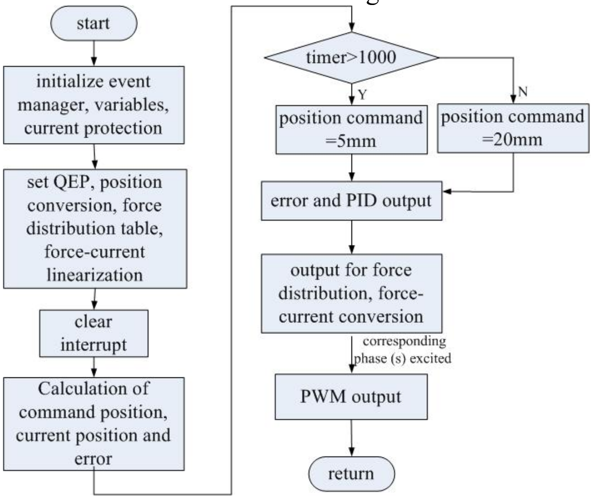
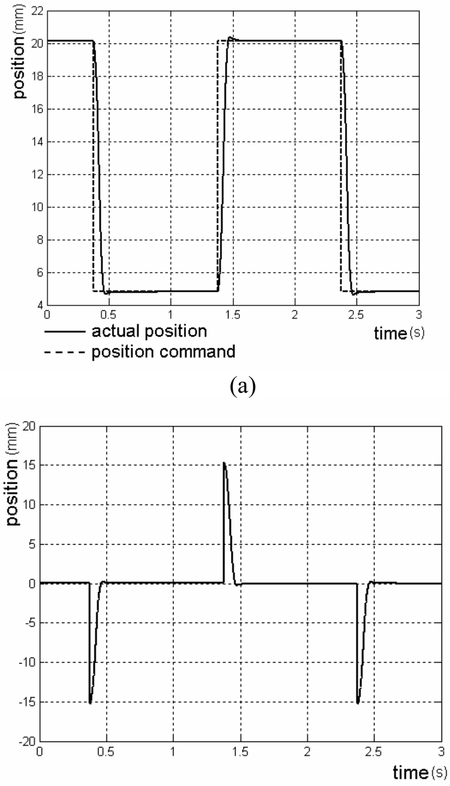


Fig.7 Software flowchart

V EXPERIMENTAL RESULTS

Under position command of square wave with amplitude 15 mm and frequency 1 Hz, the dynamic tracking profile and error is shown in Fig.8 (a) and (b), respectively. It can be concluded that the tracking profiles follow the command signal precisely with moderate overshoot and rising time. From the experimental results, the whole DSP control strategy is effective for the implementation of LSRM-based motion control system.



(a)

(b)

Fig.8 Position response (a) and dynamic error profile (b)

VI CONCLUSIONS

This paper proposes a DSP-based linear motion control system implemented with a linear switched reluctance motor, which has the characteristics of simple and robust structure, low manufacturing cost and high reliability.

Simulation results prove the simplicity of independent control strategy of each phase. With the implementation of one single digital signal processor, the position control system is established and experimental results show that the applied control system design is capable of achieving good performance for the linear motor.

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