

## Article

# Speed Control of Segmented PMLSM Based on Improved SMC and Speed Compensation Model

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**Abstract:** A segmented control model including an improved sliding model control (SMC) and a speed compensation model is applied into the speed control of a segmented permanent magnet linear synchronous motor (PMLSM) to improve the speed precision during the drive process and reduce the speed loss during the switch process. During the drive process of segmented PMLSM, an improved SMC with a disturbance observer (DOB) is used to suppress the speed fluctuation, and a DOB is added to suppress the oscillation caused by the switch part of SMC. During the switch process of a segmented PMLSM, a speed compensation model based on the position feedback of permanent magnet (PM) actuator is designed to reduce the speed loss of a segmented PMLSM, so the speed of PM actuator could be kept at the reference speed when the PM actuator absolutely quits the stator windings. Finally, the simulation and experiment are conducted to verify the control performances of proposed control model, the results indicate that the speed fluctuation of PM actuator and the speed loss during the switch process are mitigated. Therefore, this proposed control model could satisfy requirements of high-stability and celerity of segmented PMLSM in a long-distance automatic transportation system.

**Keywords:** improved sliding mode control; speed compensation; speed fluctuation; segmented permanent magnet linear synchronous motor

## 1. Introduction

The permanent magnet linear synchronous motor (PMLSM) is widely applied in long-distance automatic transportation systems because of its advantages of high-speed precision, strong reliability, fast response and great power density [1–3]. In general, the PMLSM is designed with a long stationary primary stator and a moving secondary actuator. The long stationary primary stator is filled with stator windings, and the moving secondary actuator consists of permanent magnet (PM) arrays [4]. So, the interaction between stator's magnetic field and actuator's magnetic field would make the relative movement of the secondary actuator, and then the linear motion of the PM actuator would be realized in the traveling wave magnetic field of stator winding. Furthermore, in order to reduce maintenance costs and improve the expansibility of long-distance automatic transportation systems, the modularized PMLSM model is designed as the form that multiple stage stators are arranged on the railway line with a certain gap [5,6]. Therefore, every stage stator is independently controlled by the main control unit (MCU) when the PM actuator is located on the upside of stator windings during the drive process [7], and then the PM actuator would slide on the stator part during the slide process and the switch process.

The external disturbances are easily transmitted to the secondary actuator of a PMLSM without a buffer device, so the oscillation phenomenon on thrust force of a PMLSM would occur. In addition, the mechanical vibration and shock would affect the control precision of a PMLSM [8], even the resonance possibly happen on the PM actuator at the low-frequency range. Consequently, the speed precision of the PM actuator was weakened [9]. Therefore, the suppression method for speed fluctuation should be investigated to improve the efficiency and stability of a PMLSM. Different from the normal PMLSM with continuous stator windings, the PM actuator of a segmented PMLSM is time-shared driven with three processes—the drive process, the switch process and the slide process. Especially, the effective area between the stator windings and the PM actuator is variable during the switch process, so the electromagnetic (EM) parameters such as the flux linkage and inductance deflected from theoretical values [10]. As a result, the speed fluctuation of a segmented PMLSM would be more serious and obvious than the continuous PMLSM. The research focus of this article is separated into the speed stabilization control during the drive process and the speed compensation control of a segmented PMLSM during the switch process.

During the drive process, the effective area between the stator winding and the PM actuator is constant, so the speed fluctuation is introduced by the load friction, the parameter perturbation and the detent force. Two ways were studied to suppress the speed fluctuation of a segmented PMLSM during the drive process. On the one hand, the structure optimizations of a segmented PMLSM [11,12] were conducted to reduce the oscillation on thrust force, and this part of researches were focused on optimizing structures of cogging [13], stator core [14–16], PM actuator [17] and magnetic pole [18,19]. On the other hand, different control strategies were investigated to mitigate the speed fluctuation of a segmented PMLSM. The neural network (NN) was applied to compensate the end effect of a PMLSM to minimize the fluctuation on thrust force [20–22], and the position error of a segmented PMLSM is accurately controlled at 0.28 mm. The current compensation model was designed to stabilize the thrust force of a PMLSM based on the position of the PM actuator [23,24]; the speed precision was enhanced by reducing the nonperiodic and uncertain components of detent force [23]. According to the state feedback of proportional-integral-derivative (PID) control, the adaptive feedforward compensation model was used to regulate the thrust force of a segmented PMLSM. The disturbance observer (DOB) [25,26] was used to get the periodic disturbances of a segmented PMLSM such as friction force and force ripple, and then the track precision of a segmented PMLSM was reached to 0.52  $\mu\text{m}$  in [26]. However, those above-mentioned control strategies had high requirements on the exact mathematical model of thrust force, so the accuracy of thrust force would directly affect the speed control of a segmented PMLSM. Therefore, for the purpose of suppressing the influences of uncertain thrust force on the speed control of a segmented PMLSM, the sliding model control (SMC) is used to suppress the fluctuation on thrust force of a segmented PMLSM considering its insensitivity on external disturbance and parameter variation, and then a DOB is added to suppress oscillation caused by the switch part of SMC model in this article.

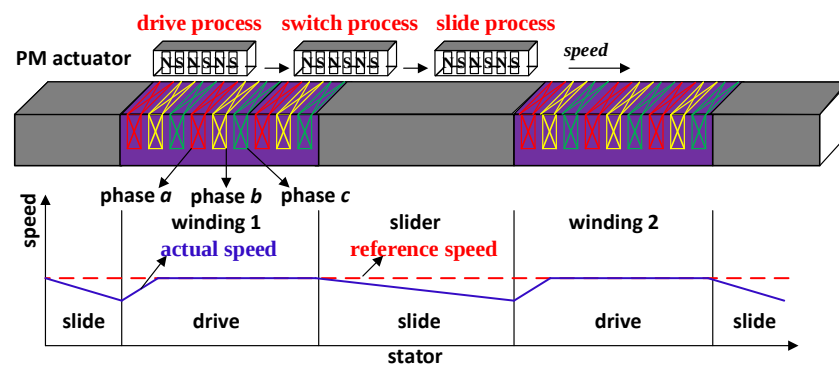
During the switch process of a segmented PMLSM, one part of PM actuator is still located in the stator winding, but another part of PM actuator had moved out of stator winding, so the variation of effective action area would lead to the variations of EM parameters and thrust force [27]. For the part of PM actuator still located in the stator winding, the thrust force would still drive the PM actuator to keep it at the reference speed. For the part of PM actuator moving out of stator winding, thrust force would prevent the PM actuator leaving from the stator winding. If the speed compensation model is not applied, the speed loss of PM actuator would be increased during the switch process. Therefore, the speed compensation control of a segmented PMLSM during the switch process is worthy of being researched to keep the speed stability and reduce speed loss of PM actuator. There was a little research about the speed compensation control of segmented PMLSM during the switch process. The flux linkage and synchronous inductance of stator winding are regarded as a linear relationship to the effective action area in almost researches [20,21,23]. Furthermore, a speed compensation model

is proposed to minimize the influence caused by the variation of EM parameters during the switch process in this article.

This article is organized as follows. The structure of segmented PMLSM is introduced in Section 2. Furthermore, an improved SMC model is designed for the segmented PMLSM during the drive process in Section 3. The speed compensation model is proposed for the segmented PMLSM during the switch process in Section 4. The numerical simulations are performed to verify the effectiveness of proposed control model used in the segmented PMLSM in Section 5. Finally, experiments are conducted to evaluate the control performances of a segmented PMLSM in Section 6.

## 2. Structure and Principle of Segmented PMLSM

The structure of segmented PMLSM is illustrated in Figure 1, there are two parts including the PM actuator part and the stator part. The PM actuator with a certain PM array is mounted on the slider of the stator part, and it is driven by the three-phase windings (phase  $a$ , phase  $b$  and phase  $c$ ) on the stator part. For the stator part, consists of the slider part and the stator winding part with the reasonable gap and length. For the motion of PM actuator, there are three stages including the drive process, the switch process and the slide process. During the drive process of PM actuator, the three-phase windings generate the thrust force to drive the PM actuator according to the reference speed. When the PM actuator moves to the gap between the stator winding and the slider, it works at switch process from the drive process into the slide process. In the slide process, the PM actuator only slides on the stator slider relied on the inertial speed, so the speed of the PM actuator would be reduced. Repeatedly, the long-distance transportation of PM actuator would be realized.



**Figure 1.** Structure and operational principle of segmented permanent magnet linear synchronous motor (PMLSM).

## 3. Model of Segmented PMLSM during Drive Process

### 3.1. Model Developing of a Segmented PMLSM

As shown in Figure 2, the control scheme of segmented PMLSM has two control loops including the  $q$ -axis loop and the  $d$ -axis loop. The position of PM actuator is measured by the magnetic scale, so the position and speed of PM actuator would be feedback to the control loop. In the speed feedback loop of segmented PMLSM, aiming at minimizing speed fluctuation caused by the external disturbances and the variation of EM parameters, an improved SMC model with an additional DOB is used to suppress the disturbances acting on the thrust force during the drive process.

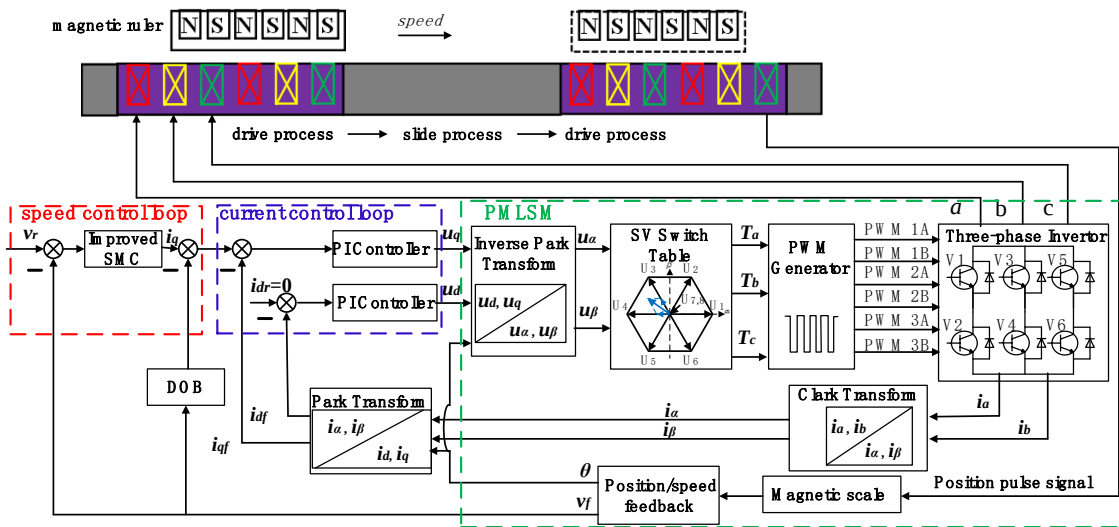


Figure 2. Control scheme of segmented PMLSM during the drive process.

For the three-phase windings of a segmented PMLSM, the vector control is applied to regulate the control currents of three-phase windings. The three-phase current in the  $abc$  coordinate is transferred into the control current in the  $dq$  coordinate, and then control voltages in the  $dq$  coordinate could be expressed into

$$\begin{cases} u_d = R_s i_d + L_d \frac{di_d}{dt} - \frac{\pi v}{\tau} \psi_q \\ u_q = R_s i_q + L_q \frac{di_q}{dt} + \frac{\pi v}{\tau} \psi_d \end{cases} \quad (1)$$

where  $R_s$  is the equivalent resistance,  $\tau$  is the polar distance and  $v$  is the speed of PM actuator.  $u_d$  is the  $d$ -axis voltage,  $u_q$  is the  $q$ -axis voltage,  $i_d$  is the  $d$ -axis current,  $i_q$  is the  $q$ -axis current,  $L_d$  is  $d$ -axis inductance,  $L_q$  is the  $q$ -axis inductance,  $\psi_d$  is the  $d$ -axis flux linkage and  $\psi_q$  is the  $q$ -axis flux linkage. For the surface mounted PMLSM, there is  $L_s = L_d = L_q$ . The flux linkage of stator winding could be expressed into

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \quad (2)$$

Substituting Equation (2) into Equation (1), the  $dq$  voltage function could be written into

$$\begin{cases} u_d + \frac{\pi v}{\tau} L_s i_q = R_s i_d + L_s \frac{di_d}{dt} \\ u_q - \frac{\pi v}{\tau} L_s i_d - \frac{\pi v}{\tau} \psi_f = R_s i_q + L_s \frac{di_q}{dt} \end{cases} \quad (3)$$

Given that the  $d$ -axis current  $i_d = 0$ , the thrust force generated by stator winding is

$$f_e = \frac{3\pi}{2\tau} p_n [\psi_f i_q + (L_d - L_q) i_d i_q] = \frac{3\pi}{2\tau} p_n \psi_f i_q = k_f i_q \quad (4)$$

where  $f_e$  is the thrust force,  $p_n$  is the polar pairs and  $k_f$  is the thrust coefficient. Therefore, when the flux linkage and the pole pairs are definite, the thrust force is positively proportional to the  $q$ -axis current.

Furthermore, the equation of motion of segmented PMLSM could be written into

$$m \frac{dv}{dt} = f_e - f_t - Bv \quad (5)$$

where  $m$  is mass of PM actuator,  $f_t$  is the disturbance force including friction force and detent force,  $B$  is coefficient of viscous friction.

The state variable is chosen as  $x = [f_t \ i_d \ i_q \ v]^T$ , and given that  $i_d = 0$  and  $u_d = 0$ , the state space function of segmented PMLSM could be written into

$$\dot{x} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{-R_s}{L_s} & \frac{\pi\psi_f}{\tau L_s} \\ \frac{-1}{m} & 0 & \frac{3\pi p_n \psi_f}{2\tau m} & \frac{-B}{m} \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ \frac{-1}{L_s} \\ 0 \end{bmatrix} u_q \quad (6)$$

$$y = [0 \ 0 \ 0 \ 1] x \quad (7)$$

### 3.2. SMC Model of a Segmented PMLSM during Drive Process

As illustrated in Figure 3, in order to suppress the speed fluctuation of segmented PMLSM caused by the parameter perturbation and the detent force during the drive process, an SMC model including equivalent control part and switch control part is applied. For the switch control part of SMC, the chattering phenomena would occur when the PM actuator works at the switch process from the drive process into the slide process. Therefore, the saturation function is applied in the switch control part of SMC by replacing the normal sign function, and a DOB is added to reduce the gain of switch control part of SMC.

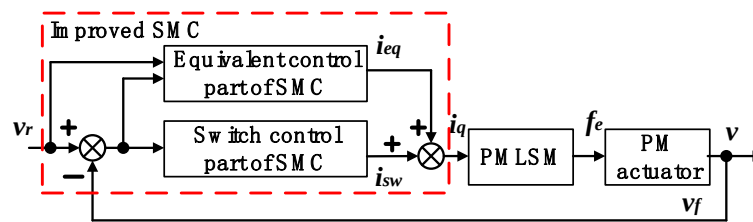


Figure 3. The sliding model control (SMC) model of segmented PMLSM.

Combining Equations (4) and (5), the equation of motion of PM actuator with parameter perturbation could be expressed into

$$k_f i_q = (m + \Delta m) \frac{dv}{dt} + f_t + (B + \Delta B)v \quad (8)$$

where  $\Delta m$  is the mass perturbation of PM actuator, and  $\Delta B$  is uncertain coefficient of viscous friction.

The generalized disturbance term is defined as

$$f_r = \Delta m \frac{dv}{dt} + f_t + \Delta Bv \quad (9)$$

The error between the reference speed and the actual speed is

$$e(t) = v_r - v_f \quad (10)$$

By differentiating speed error, there is

$$\begin{aligned} \dot{e}(t) &= -\frac{dv}{dt} = -\frac{k_f}{m} i_q + \frac{B}{m} v + \frac{f_r}{m} = \frac{-B}{m} (v_r - v_f) - \frac{k_f}{m} i_q + \frac{f_r}{m} + \frac{B}{m} v_r \\ &= P e(t) + Q i_q + R f_r - P v_r \end{aligned} \quad (11)$$

where  $P = \frac{-B}{m}$ ,  $Q = \frac{-k_f}{m}$ ,  $R = \frac{1}{m}$ .

For the purpose of enhancing the stability, the sliding face function is chosen as the following

$$s(e) = c \int_{-\infty}^t e(\tau) d\tau + e(t) = cI_0 + c \int_0^t e(\tau) d\tau + e(t) \quad (12)$$

So, the speed of the system approaching stability decreases with the value of  $c$ . The initial condition is

$$s(e)|_{t=0} = cI_0 + 0 + e(0) = 0 \xrightarrow{\text{yields}} I_0 = -\frac{e(0)}{c} = -\frac{v_r}{c} \quad (13)$$

When the control model is switched into the sliding mode surface, there is  $s(e) = 0$ , the differential function of Equation (12) could be expressed into

$$\dot{e}(t) + ce(t) = 0 \quad (14)$$

Then the static error of speed could be solved as

$$e(t) = E_0 e^{-ct} \quad (15)$$

Given the condition that  $c > 0$ , there is

$$\lim_{t \rightarrow \infty} e(t) = \lim_{t \rightarrow \infty} E_0 e^{-ct} = 0 \quad (16)$$

Based on the equivalent control conditions as following

$$\begin{cases} \frac{ds(e)}{dt} = 0 \\ f_r = 0 \end{cases} \quad (17)$$

Substituting Equations (4) and (17) into Equation (11), the equivalent control function of SMC is achieved as following

$$i_{eq} = \frac{-m}{k_f} \left[ \frac{-B}{m} v_r + \left( c - \frac{B}{m} \right) e(t) \right] = \frac{1}{Q} [Pv_r + (c + P)e(t)] \quad (18)$$

The switch control function of SMC is chosen as following

$$i_{sw} = k \cdot \text{sat} \left( \frac{s(e)}{\phi} \right) = \begin{cases} k, & s \geq \phi \\ k \frac{s(e)}{\phi}, & \phi < s < -\phi \\ -k, & s \leq -\phi \end{cases} \quad (19)$$

where  $k$  is the gain of switch control part,  $\text{sat}()$  is the saturation function and  $\phi$  is the thickness of boundary layer.

Finally, the control law of SMC could be synthesized into

$$i_q = i_{eq} + i_{sw} = \frac{1}{Q} [Pv_r + (c + P)e(t)] + k \cdot \text{sat} \left( \frac{s(e)}{\phi} \right) \quad (20)$$

In order to keep the stability of SMC model, the Lyapunov function is defined as

$$\dot{V} = s(e)\dot{s}(e) < 0 \quad (21)$$

Substituting Equations (11), (12), (14) and (20) into Equation (21), there is

$$\begin{aligned}\dot{V} &= s(e)\dot{s}(e) = s(e)(ce(t) + \dot{e}(t)) = s(e)[ce(t) + Pe(t) + Qi_q + Rf_r - Pv_r] \\ &= kQs(e) \cdot \text{sat}\left(\frac{s(e)}{\phi}\right) + Rf_r s(e) < 0\end{aligned}\quad (22)$$

Therefore, the gain of switch control part is achieved as

$$k > \frac{-Rf_r}{Q \cdot \text{sat}\left(\frac{s(e)}{\phi}\right)} = \frac{\max|f_r|}{k_f} \quad (23)$$

Therefore, the stability of SMC model can be guaranteed when the gain of the switch control part satisfies the condition in Equation (23).

### 3.3. Improved SMC Model of a Segmented PMLSM during Drive Process

Furthermore, according to Equations (6) and (7), the augmented form of state space function including the disturbance term could be written into

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} u_q \quad (24)$$

$$y = \begin{bmatrix} 0 & C \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad (25)$$

where  $x_1 = f_t$  and  $x_2 = [i_d \ i_q \ v]^T$ ,  $A_{11} = 0$ ,  $A_{12} = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}$ ,  $A_{21} = \begin{bmatrix} 0 \\ 0 \\ \frac{-1}{m} \end{bmatrix}$ ,  $A_{22} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{-R_s}{L_s} & \frac{\pi\psi_f}{\tau L_s} \\ 0 & \frac{3\pi p_n \psi_f}{2\tau m} & \frac{-B}{m} \end{bmatrix}$ ,

$B_1 = 0$ ,  $B_2 = \begin{bmatrix} 0 \\ \frac{-1}{L_s} \\ 0 \end{bmatrix}$ ,  $C$  is the unit matrix. Furthermore, the rank of matrix  $\begin{bmatrix} C & CA_{22} & CA_{22}^2 \end{bmatrix}$  is 3,

and the rank of matrix  $\begin{bmatrix} A_{22} & A_{21} \\ C & 0 \end{bmatrix}$  is 4, so the augmented matrix is observable. In addition, the state variable  $x_2$  is measurable. Therefore, a reduced-order DOB could be designed to observe the disturbance term.

The state space function with reduced-order DOB could be expanded into

$$\begin{cases} \dot{x}_1 = A_{11}x_1 + A_{12}x_2 + B_1u_q = A_{11}x_1 + A_{12}y + B_1u_q \\ \dot{x}_2 = \dot{y} = A_{12}x_1 + A_{22}x_2 + B_2u_q = A_{12}x_1 + A_{22}y + B_2u_q \end{cases} \quad (26)$$

Defining  $y' = \dot{y} - A_{22}y - B_2u_q$ , Equation (26) could be rewritten into

$$\begin{cases} \dot{x}_1 = A_{11}x_1 + (A_{12}y + B_1u_q) \\ y' = A_{12}x_1 \end{cases} \quad (27)$$

The state observation function could be expressed into

$$\dot{\hat{x}} = (A_{11} + HA_{21})\hat{x}_1 + (A_{12}y + B_1u_q) - Hy' \quad (28)$$

where  $H = [h_1 \ h_2 \ h_3]$  is the correction matrix.

Defining the variable substitution  $z = \hat{x}_1 + Hy'$ , there are

$$\dot{z} = (A_{11} + HA_{21})z + (B_1 + HB_2)u_q + [A_{12} + HA_{22} - (A_{11} + HA_{21})H]y' \quad (29)$$

$$\hat{F}_r = z - Hy' \quad (30)$$

where  $(A_{11} + HA_{21}) = 0 + \begin{bmatrix} h_1 & h_2 & h_3 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{m} \end{bmatrix} = \frac{-h_3}{m} < 0$ .

Finally, Equation (29) would be rewritten into

$$\dot{z} = -\frac{h_3}{m}z + \frac{3\pi p_n \psi_f h_3}{2\tau m} i_q + \left( \frac{h_3^2}{m} - \frac{Bh_3}{m} \right) v \quad (31)$$

$$\hat{F}_r = z - h_3 v \quad (32)$$

By introducing the filter time constant  $\frac{1}{T_0} = \frac{h_3}{m}$ , Equation (31) could be rewritten into

$$\dot{z} = -\frac{1}{T_0}z + \frac{3\pi p_n \psi_f}{2\tau T_0} i_q + \left( \frac{h_3}{T_0} - \frac{B}{T_0} \right) v \quad (33)$$

The observed value of disturbance is

$$\hat{f}_r = \frac{3\pi}{2\tau(T_0 s + 1)} p_n \psi_f i_q - \frac{B}{(T_0 s + 1)} v - \frac{m}{(T_0 s + 1)} \frac{dv}{dt} \quad (34)$$

Therefore, as illustrated in Figure 4, the improved SMC model combining an SMC model and a DOB model could be used into speed control of segmented PMLSM during the drive process.

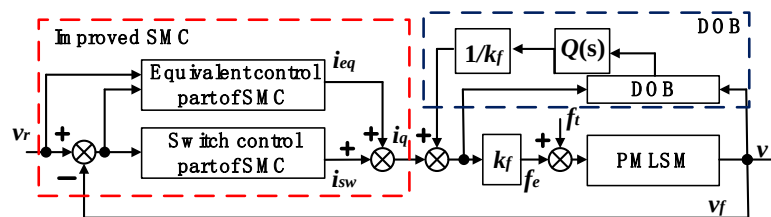


Figure 4. The improved SMC model of segmented PMLSM.

#### 4. Model of Segmented PMLSM during the Switch Process

During the switch process, the thrust force generated by the stator winding is declined, and then the speed of the PM actuator would be affected. Consequently, the speed precision of PM actuator and the efficiency of segmented PMLSM are disturbed. As shown by the green square in Figure 5, the speed compensation model is applied to minimize the speed loss during the switch process. The speed and position of PM actuator are measured by the magnetic scale mounted on the stator part. For the EM parameter calculation of segmented PMLSM during the switch process, the flux linkage of segmented PMLSM at the boundary of stator winding is

$$\begin{cases} \psi_{fin}(x) = \frac{x}{l_a} \psi_f, & 0 < x < l_a \\ \psi_{fout}(x) = \frac{l_s + l_a - x}{l_a} \psi_f, & l_s < x < l_s + l_a \end{cases} \quad (35)$$

where  $x$  is the actual position of PM actuator,  $l_a$  is the length of PM actuator,  $l_s$  is the length of stator,  $\psi_f$  is the flux linkage of stator winding when the PM actuator is at the drive process and  $\psi_{fin}(x)$  and  $\psi_{fout}(x)$  are the flux linkage when the PM actuator moves in and out of stator winding, respectively.



where  $\beta$  is the bandwidth of speed control loop, and it could be achieved through the pole placement of (40).

Combing Equations (40) and (41), the coefficient of active damping is

$$B_a = \frac{2\tau(\beta m - B)}{3\pi p_n \psi_f(x)} \quad (42)$$

The PI model is used in the speed control loop and the current control loop. Based on reference [28], the PI parameters of speed control loop are chosen as

$$\begin{cases} K_{pv} = \frac{3\beta m}{2p_n \psi_f(x)} \\ K_{iv} = \beta K_{pv} \end{cases} \quad (43)$$

For the current control loop, the PI parameters in  $d$ -axis control loop are chosen as

$$\begin{cases} K_{pd} = \alpha L_d(x) \\ K_{id} = \alpha R \end{cases} \quad (44)$$

The PI parameters in  $q$ -axis current loop are chosen as

$$\begin{cases} K_{pq} = \alpha L_q(x) \\ K_{iq} = \alpha R \end{cases} \quad (45)$$

where  $\alpha$  is the bandwidth of current control loop, and it is

$$\alpha = \max\left\{ \frac{2\pi R}{L_d(x)}, \frac{2\pi R}{L_q(x)} \right\} \quad (46)$$

Therefore, the output current of speed control loop through the anti-current saturation compensation model is

$$i'_q = \left( K_{pv} + \frac{K_{iv}}{s} \right) (v' - v) - B_a v \quad (47)$$

Above all, the speed compensation of PM actuator could be realized by timely regulating the control parameters based on the EM coefficients of stator winding during the switch process.

## 5. Numerical Simulation

In the simulation, the speed control of PM actuator during the drive process and the switch process is conducted, and the parameters of segmented PMLSM are listed in Table 1.

**Table 1.** Parameters of a segmented PMLSM.

| Symbol     | Quantity                             | Value         |
|------------|--------------------------------------|---------------|
| $P_n$      | Poles pairs                          | 5             |
| $m$        | Mass of the PM actuator              | 5 kg          |
| $B$        | Coefficient of viscous friction      | 0.3           |
| $L_s$      | Self-inductance of stator winding    | 4.6 mH        |
| $L_\sigma$ | Leakage inductance of stator winding | 2.0 mH        |
| $\tau$     | Polar distance                       | 20 mm         |
| $\psi_f$   | Flux linkage of the PM actuator      | 0.2 Wb        |
| $v_r$      | Reference speed of the PM actuator   | 0.5 m/s       |
| $l_a$      | Length of the PM actuator            | 0.2 m         |
| $R_s$      | Resistance of stator winding         | 4.35 $\Omega$ |
| $l_s$      | Length of single stator              | 0.4 m         |
| $\alpha$   | Bandwidth of current control loop    | 3 kHz         |
| $\beta$    | Bandwidth of speed control loop      | 6 kHz         |

### 5.1. Detent Force of Stator Winding

According to the finite element method, the relationship between the detent force of stator winding and the position of PM actuator is plotted in Figure 6, the length period of detent force is equal to the polar distance  $\tau$ . So, the detent force of stator winding could be expressed with terms of PM actuator's position and polar distance as following

$$f_d(x) \approx 1.44 - 8.23 \sin(100\pi x - 0.21\pi) + 2 \sin(200\pi x + 0.17\pi) + 1.67 \sin(300\pi x + 0.11\pi) + 0.54 \sin(400\pi x + 0.25\pi) \quad (48)$$

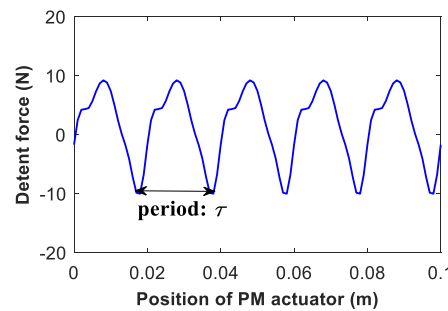
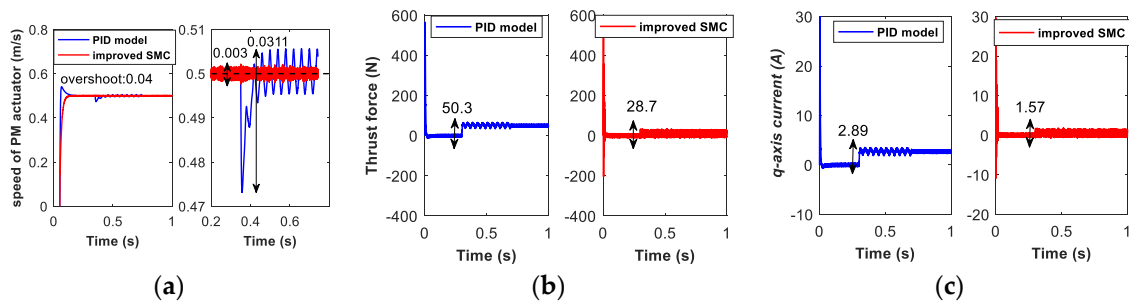


Figure 6. Detent force of segmented PMLSM.

It is obvious that the detent force of stator winding is a periodic function about the position of PM actuator.

### 5.2. Control Performance of a Segmented PMLSM during Drive Process

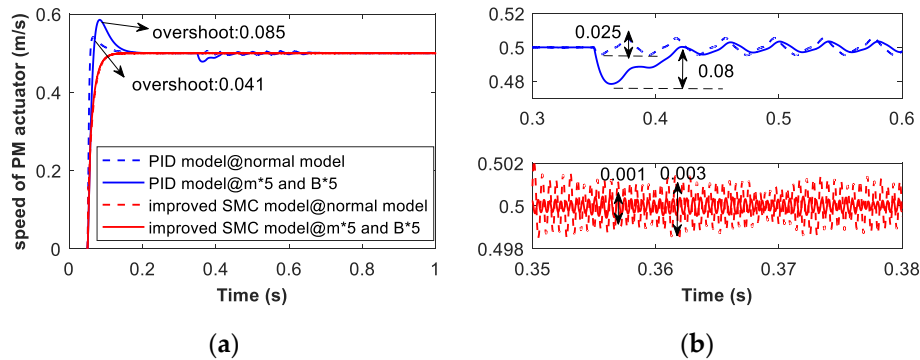
Furthermore, for the PID control model, control parameters in the speed loop of  $q$ -axis control loop are chosen as  $K_{pv} = 500$  and  $K_{iv} = 100$ , control parameters in the current loop of  $q$ -axis control loop are  $K_{pi} = 100$  and  $K_{ii} = 3000$ , the control parameters in the current loop of  $d$ -axis control loop are  $K_{pd} = 500$  and  $K_{id} = 100$ . The parameters of improved SMC model are chosen as following,  $c = 60$ ,  $k = 100$ ,  $h_3 = 5000$  and  $T_0 = 0.0011$  s. The speed curves of segmented PMLSM with different control models are plotted in Figure 7a, the step signal with 0.5 m/s is chosen as the reference speed of segmented PMLSM, and the detent force is used as the disturbance force at  $t = 0.4$  s. For the speed curve of PM actuator with the PID model, as shown by the blue line, the overshoot is about 0.04 m/s, and the response magnitude for disturbance force is about 0.0311 m/s. For the speed curve of PM actuator with the improved SMC model as marked by the red line, the overshoot for reference input is effectively suppressed, and the response magnitude for disturbance force is about 0.003 m/s. In addition, the thrust forces and  $q$ -axis currents of segmented PMLSM with different models are illustrated in Figure 7b,c, respectively. The response magnitude of thrust force and  $q$ -axis current are consistent with the response magnitude of speed curve, the greater magnitude of speed curve would lead to the greater variations of thrust force and  $q$ -axis current during the drive process.



**Figure 7.** (a) Speed curves of segmented PMLSM with different models, (b) thrust forces of segmented PMLSM with different models and (c)  $q$ -axis currents of segmented PMLSM with different models.

### 5.3. Speed Curves of a Segmented PMLSM with Parameter Perturbation during the Drive Process

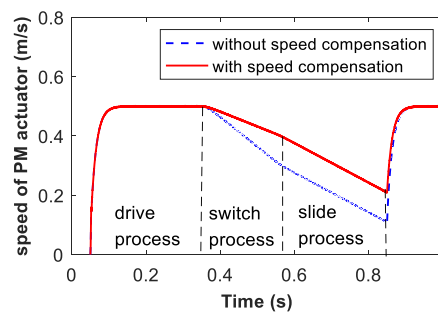
With the parameter perturbation of segmented PMLSM on the mass of PM actuator and the viscous friction, where the mass of PM actuator increases to  $5 \times m$  and the viscous friction coefficient increases to  $5 \times B$ , the speed curves of PM actuator are shown in Figure 8. For the PID model as shown by the blue line, the overshoot is increased from 0.041 m/s to 0.085 m/s, and the response magnitude for disturbance force (10% of gravity of the PM actuator) is increased from 0.025 m/s to 0.08 m/s. For the improved SMC model as shown by the red line, the overshoot is kept at zero, and the response magnitude for disturbance force is increased from 0.001 m/s to 0.003 m/s. Therefore, the comparison indicates that the improved SMC model designed for segmented PMLSM could improve the speed precision and anti-disturbance by reducing the overshoot amount and the disturbance response.



**Figure 8.** Speed curve of segmented PMLSM with parameter perturbation and different models, (a) speed curves and (b) disturbance response.

### 5.4. Speed Curves of a Segmented PMLSM during the Switch Process

The speed curves of PM actuator during the switch process are plotted in Figure 9, the speed of PM actuator is accelerated to the rate speed and then the speed would be decelerated during the switch and slide process. The blue line presents the speed curve of PM actuator without the speed compensation model, and the red line is the speed curve of PM actuator with the speed compensation model. During the switch process, the speed of PM actuator with the speed compensation model is decelerated from 0.5 m/s to 0.405 m/s, and it is reduced from 0.5 m/s to 0.307 m/s without speed compensation model. Therefore, the speed of PM actuator could be effectively compensated by the speed compensation model during the switch process, and then speed loss is reduced.



**Figure 9.** Speed curves of segmented PMLSM during switch process.

Above all, the performance comparisons of segmented PMLSM with PID model and improved SMC model are listed in Table 2. This result indicates that the improved SMC model of segmented PMLSM could improve the speed precision and the robustness stability, and then the speed loss of PM actuator during the switch process is reduced by using the speed compensation model.

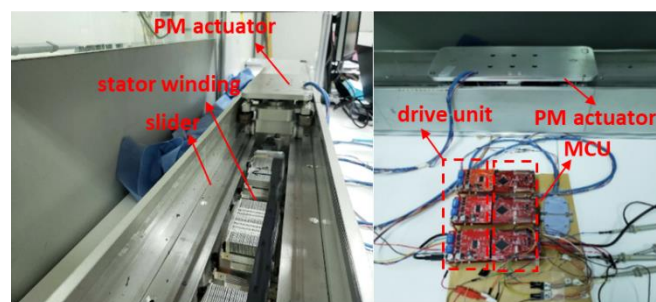
**Table 2.** Simulation performances of segmented PMLSM with proportional-integral-derivative (PID) and improved SMC model.

| Simulation Situation                      | PID Model | Improved SMC Model |
|-------------------------------------------|-----------|--------------------|
| Overshoot of reference response (m/s)     | 0.04      | 0                  |
| Response for detent force (m/s)           | 0.0311    | 0.03               |
| Thrust force for detent force (N)         | 50.3      | 28.7               |
| Q-axis current for detent force (A)       | 2.89      | 1.57               |
| Overshoot of parameter perturbation (m/s) | 0.085     | 0                  |
| Response of parameter perturbation (m/s)  | 0.08      | 0.003              |
| Response during switch process (m/s)      | 0.405     | 0.307              |

## 6. Experiment

### 6.1. Experimental Setup

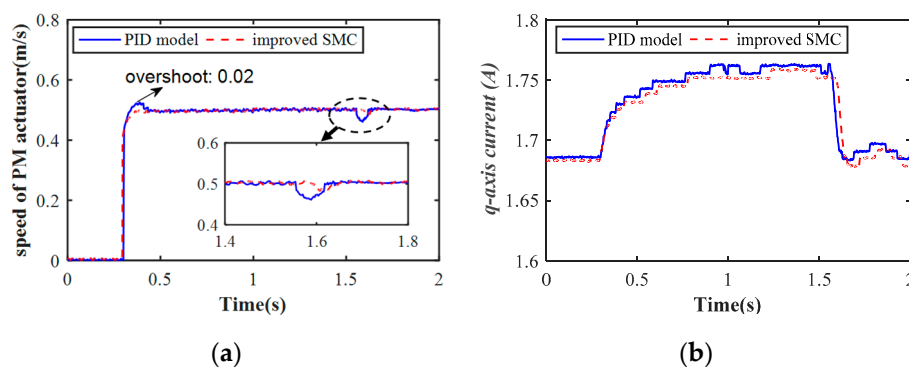
The whole experimental setup of segmented PMLSM is shown in Figure 10. There are three parts including the stator part, the PM actuator and the MCU. The stator part was separated into the stator winding and the slider. The position of the PM actuator could be recorded timely by the magnetic scale (SIKO MSK5000AS) mounted on the stator part. The MCU based on the digital signal processor TMS320F28377 could receive the position/speed signals of PM actuator, send the control signal to the drive unit (DRV8301) with control frequency 10 kHz and then the thrust force generated by the stator winding could be regulated. The photoelectric switches (model EE-SY671) were mounted at the ends of stator winding and slider; the control methods of segmented PMLSM during different processes were timely switched based on the captured switching signal of photoelectric switch.



**Figure 10.** The experimental setup of segmented PMLSM.

### 6.2. Speed Curves of a Segmented PMLSM during the Drive Process

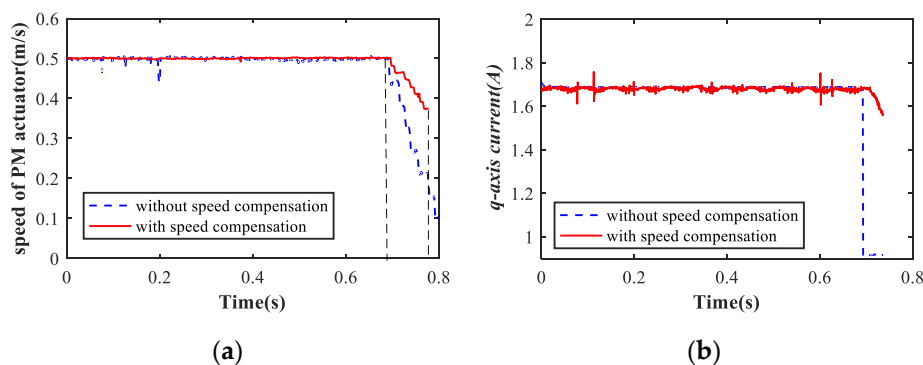
In this part of the experiment, the step signal with 0.5 m/s was chosen as the reference speed signal, and a pulse-type disturbance with 10% of gravity of PM actuator (generated by the impact hammer) imposed on it. The speed curves and the  $q$ -axis current of segmented PMLSM were measured and compared during the drive process. As illustrated in Figure 11a, the speed curve of PM actuator with the PID model is shown by the blue line, the overshoot amount is 0.02 m/s, and the response magnitude for disturbance is 0.04 m/s. For the improved SMC model as marked by the red line, the response magnitude for disturbance is 0.02 m/s. In the meanwhile, the  $q$ -axis current of segmented PMLSM are plotted in Figure 11b. The  $q$ -axis current of segmented PMLSM with the improved SMC model is smaller than that with the PID model, and the reduction is 0.01A. Therefore, the improved SMC model designed for segmented PMLSM could suppress the speed fluctuation and reduce the current oscillation during the drive process.



**Figure 11.** (a) Speed curves of segmented PMLSM with different models during drive process; (b)  $q$ -axis currents of segmented PMLSM with different models during drive process.

### 6.3. Speed Curves of a Segmented PMLSM during the Switch Process

Furthermore, the speed curves of segmented PMLSM with different control models during the switch process are plotted in Figure 12a. For the speed curve of PM actuator without the compensation model, as shown by blue line, the speed loss within 0.1 s is about 0.3 m/s, but speed loss with the compensation model is reduced to 0.13 m/s. Moreover, the  $q$ -axis currents of segmented PMLSM during the switch process are plotted in Figure 12b. For the  $q$ -axis current without speed compensation model, it would drop to a low value when the PM actuator moved from the drive process into the switch process. The  $q$ -axis current of segmented PMLSM with the speed compensation model could keep at a relatively high level to continually drive the PM actuator. Therefore, the speed loss of segmented PMLSM could be effectively reduced by the speed compensation model.



**Figure 12.** (a) Speed curves of segmented PMLSM with different models during switch process; (b)  $q$ -axis current of segmented PMLSM with different models during switch process.

## 7. Conclusions

The segmented PMLSM used in the long-distance auto transportation system is easily suffered from the external disturbances and the variation of EM parameters. An improved SMC with a DOB model is designed to minimize the disturbance on the speed precision of the PM actuator during the drive process, and the speed compensation model is used to reduce the speed loss of the PM actuator during the switch process. The simulation and experiment both verify that the speed precision of PM actuator with the improved SMC model is improved, and fluctuations of thrust force and control current are effectively suppressed. Moreover, the speed loss of PM actuator during the switch process is minimized by the speed compensation model. Therefore, even though the oscillation phenomenon caused by DOB is not eliminated but mitigated, the segmented control model used in segmented PMLSM is the potential to improve the control precision and efficiency of long-distance auto transportation systems.

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