Sensorless Control of Segmented PMLSM for Long-Distance Auto-Transportation System Based on Parameter Calibration

TONG WEN\textsuperscript{1,2}, ZHONGYI WANG\textsuperscript{1}, BIAO XIANG\textsuperscript{3}, BANGCHENG HAN\textsuperscript{1}, (Member, IEEE), AND HAITAO LI\textsuperscript{1}, (Member, IEEE)

\textsuperscript{1}School of Instrumentation and Optoelectronic Engineering, Beihang University, Beijing 100191, China
\textsuperscript{2}Ningbo Institute of Technology, Beihang University, Ningbo 315000, China
\textsuperscript{3}Department of Mechanical Engineering, The Hong Kong Polytechnical University, Hong Kong

Corresponding author: Biao Xiang (thomas.biao@gmail.com)

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ABSTRACT The permanent magnet linear synchronous motor (PMLSM) with segmented stator is applied in the long-distance auto-transportation system. For the PMLSM with the discontinuous stators, the mismatch between the permanent magnet (PM) mover and the stator would make electromagnetic (EM) parameters deflect nominal values, and then position/speed precision of the PM mover would be affected. In this article, the sensorless control based on the parameter calibration is used to drive the PM mover above the segmented stators during the drive process. Furthermore, an improved model reference adaptive integrator based on the parameter calibration is proposed to calibrate the EM parameters during the switch process. The simulation and experimental results confirm that the speed precision and the robustness of the segmented PMLSM are enhanced distinctly.

INDEX TERMS PMLSM, segmented stator, parameter calibration, sensorless control.

I. INTRODUCTION

The auto-transportation system is widely used in factory automation because of its advantages on fast response speed and great capacity. In general, the traditional auto-transportation system adopts the mechanical conversion system to transfer rotational motion into linear motion, but this kind of auto-transportation system could not satisfy requirements on rapidity, high efficiency, great load capacity and low energy consumption [1]. Therefore, the permanent magnet linear synchronous motor (PMLSM) is widely used in the auto-transportation system due to its advantages on high reliability, high motor efficiency and great power density [2]–[4]. However, the stators in the continuous PMLSM are usually continuously connected and arranged on the transportation rail, so the flexibility of the continuous PMLSM is weakened and the initial cost is increased in the long-distance auto-transportation system [5]. In order to solve this problem, a new structure of PMLSM with discontinuous stators is becoming the research focus of the long-distance auto-transportation system [4], [6]–[11].

For the purpose of reducing the high cost of sensors and improving the robust stability of the segmented PMLSM, the sensorless control method was proposed in the segmented PMLSM system [12]–[15]. The back electromotive force (EMF) integration method was often used in the sensorless control of the PMLSM [16], [17], but it exhibited poor estimation accuracy at low speed and had obvious integral drift. The sensorless control method based on the high-frequency signal injection was also studied [18], and it was applied to the stator winding by superimposing a high-frequency voltage on the fundamental wave signal. So, the position information was obtained through resolving the corresponding high-frequency current, and then the position signal could be achieved by the band-pass filter. However, this method had strict requirements on the saliency ratio of motor. Furthermore, the extended Kalman filter [19], the unscented Kalman filter [20] and the sliding mode observer [21], [22] were usually used to improve the performance of the sensorless control. Nevertheless, since a large amount of calculation were unavoidable in those control methods, they were not...
suitable for the long-distance auto-transportation system. Some scholars began to adopt the artificial intelligence algorithms to the sensorless control in order to get better control performance [23], [24], but this technology was not mature enough in the control engineering of the segmented PMLSM used in the long-distance auto-transportation system.

Moreover, due to the discontinuity of the stator part in the segmented PMLSM, the PM mover must pass different stator parts frequently. Owing to the assembly error between the segmented stator and the PM mover, the electromagnetic (EM) parameters of the segmented PMLSM are not constant values, so the precision of position estimation would be affected. Therefore, it is necessary to calibrate the EM parameters before the control model of the segmented PMLSM is switched from the normal control model into the sensorless control during the switch process. Many methods about the parameter calibration were used to justify the EM parameters of the segmented PMLSM. The least square method was proposed to calibrate the stator resistance and the synchronous inductance under the assumption that the permanent magnet (PM) flux linkage is constant [25], but it did not eliminate the influence of parameter variation on the identification precision. The parameter calibration was also realized by injecting the short-time alternating current (AC) disturbance [26], but the torque ripple was easily excited. An adaptive parameter identification algorithm based on an improved cooperative particle swarm optimization was used for the parameter identification [27]. Nevertheless, it was not suitable for the segmented PMLSM used in the long-distance auto-transportation system because of the high complexity and the extensive calculation. An online parameter identification method was proposed for the segmented PMLSM based on the real-time back EMF voltages and the speed of the PM mover, and it could quickly calibrate the flux linkages and the synchronous inductance before the PM mover entirely coincides with the stator part [28], so the EM parameters could be regulated in the sensorless control of the segmented PMLSM after the parameter calibration.

Above all, the position precision of the PM mover is distinctly affected by the variations of EM parameters because the PM mover and the segmented stators are not fixedly paired during the switch process. Therefore, the sensorless control is innovatively combined with the parameter calibration to reduce the influence of EM parameter variation on control performance in this article, and an improved integrator based on the model reference adaptive principle is used to improve the estimation precision and the robustness.

This article is organized as follows. In section II, the model of the segmented PMLSM is developed, and the influences of EM parameter variation on the sensorless control are analyzed. The specific principles of the parameter calibration and the sensorless control are designed in section III. The section IV introduces the simulation and experimental results to validate effectiveness of the proposed control method. Some essential conclusions are summarized in section V.

II. MODELING OF SEGMENTED PMLSM SYSTEM

The structure of the segmented PMLSM is shown in FIGURE 1, and it is consisted of the primary stator and the secondary PM mover. For the primary stator part, the stators with driving coils and the rails without driving coils are placed alternatively according to the length ratio. For the PM mover, there are three motion processes including the drive process, the switch process and the slide process. The PM mover is totally above the stator with driving coils during the drive process, and it would be accelerated to the rate speed. When one part of the PM mover is above the stator with driving coils and another part of the PM mover is on the rail without driving coils, the segmented PMLSM works at the switch process. The slide process happens when the PM mover entirely slides on the rail without driving coils. Each stator with driving coils has its independent drive module during the drive and switch process.

As like the rotary electric motor, the coordinate system of the PM mover in the segmented PMLSM could be presented in FIGURE 2. The voltage equations of the PM mover in $\alpha\beta$ axes are

$$ \begin{align*}
    u_\alpha &= R_s i_\alpha + L_\alpha \frac{di_\alpha}{dt} - \frac{\psi_f}{\tau} \frac{\pi \varphi}{\sin \theta} \\
    u_\beta &= R_s i_\beta + L_\beta \frac{di_\beta}{dt} + \frac{\psi_f}{\tau} \frac{\pi \varphi}{\cos \theta}
\end{align*} $$

(1)

where $u_\alpha$ and $u_\beta$ are stator voltages in $\alpha\beta$ axes, $R_s$ is the stator resistance, $i_\alpha$ and $i_\beta$ are stator currents in $\alpha\beta$ axes, $L_\alpha$ and $L_\beta$ are inductances in $\alpha\beta$ axes, $\varphi$ is the speed of the PM mover, and $\tau$ is the pole pitch, and $\psi_f$ is the PM flux linkage.

The flux linkage equations in $\alpha\beta$ axes could be written as

$$ \begin{align*}
    \psi_\alpha &= \int (u_\alpha - R_s i_\alpha) dt \\
    \psi_\beta &= \int (u_\beta - R_s i_\beta) dt
\end{align*} $$

(2)
Combing (1) and (2), we could get
\[
\begin{align*}
\psi_\alpha &= L_\alpha i_\alpha + \psi_f \frac{\pi}{\tau} \cos \theta \\
\psi_\beta &= L_\beta i_\beta + \psi_f \frac{\pi}{\tau} \sin \theta
\end{align*}
\]  
\tag{3}

The basic integration equations of the speed and position are
\[
\begin{align*}
v &= \frac{\tau}{\pi} \omega_r = \frac{\tau}{\pi} \frac{d\theta_r}{dt} \\
x &= \int v dt = \frac{\tau}{\pi} \theta_r = \frac{\tau}{\pi} \arctan \left( \frac{\psi_\beta - L_\beta i_\beta}{\psi_\alpha - L_\alpha i_\alpha} \right)
\end{align*}
\tag{4}
\]

where $x$ is the estimated position of the PM mover, $\psi_\alpha$ and $\psi_\beta$ are the flux linkages in $\alpha\beta$ axes. Therefore, the estimation accuracies of the position and speed are directly affected by the inductance and the flux linkage, so it is necessary to calibrate the EM parameters of the segmented PMLSM to tune control parameters during the switch process.

The whole control scheme of the segmented PMLSM is shown in FIGURE 3, there are two control loops including the speed control loop and the current control loop. For measurement system of the segmented PMLSM, the magnetic ruler is fixed at the bottom of the PM mover, and the reading heads at two ends of stator and rail could detect motion process of the PM mover, and then the parameter calibration is determined by the position signal captured by the reading heads. On the other hand, the control process of the PM mover has two parts including the parameter calibration module and the sensorless control module. When the PM mover enters the stator with driving coils, the speed of the PM mover is measured by the magnetic ruler, and the back EMF voltage and the electric angle are recorded by the current sampling circuit. Furthermore, the EM parameter calibration is conducted to calibrate the stator inductance and the flux linkage, and then the control parameters could be updated in different motion process of the PM mover.

As shown in FIGURE 4, the back EMF voltages of the segmented PMLSM vary with the coupling area between the PM mover and the stator when the PM mover passes the stator at a constant speed, the back EMF voltage would increase with the coupling area during the drive process and the switch process. Therefore, the flux linkages of the segmented PMLSM could be achieved through the back EMF voltages.
According to the Faraday’s law of electromagnetic induction, the back EMF voltages of the segmented PMLSM could be described as

\[
\begin{align*}
e_A &= P \cos \theta \\
e_B &= P \cos \left( \theta - \frac{2}{3} \pi \right) \\
e_C &= P \cos \left( \theta + \frac{2}{3} \pi \right)
\end{align*}
\]  

(5)

Furthermore, the \(e_a\), \(e_B\) in the static coordinate could be obtained by the Clark transformation. Then, the amplitude \(P\) could be obtained by

\[
P = \sqrt{e_a^2 + e_B^2}
\]

(6)

The PM flux linkage \(\psi_f\) could be calculated as

\[
\psi_f = \frac{\tau}{\pi} e_0 v
\]

(7)

where \(e_0\) is no-load back EMF, and it could be achieved as

\[
e_0 = \sqrt{3} E_0
\]

(8)

where \(E_0 = P f / \sqrt{2}\).

Therefore, the flux linkage \(\psi_f\) could be obtained by

\[
\psi_f = \sqrt{\frac{3}{2}} P \tau
\]

(9)

Moreover, the PM flux linkage \(\psi_f\) is the product of the PM equivalent excitation inductance \(L_m\) and the PM equivalent current \(i_f\), and the equivalent excitation inductance is

\[
L_m = \frac{\psi_f}{i_f}
\]

(10)

where \(i_f = H_c / h_m\), and \(H_c\) is the coercivity of the PM mover, and \(h_m\) is the magnetism length of the PM mover.

Since the structure of the segmented PMLSM is surface-mounted type, the leakage inductance \(L_{ss}\) is a constant, and the synchronous inductance is

\[
L_s = L_{ss} + L_m
\]

(11)

Therefore, the PM flux linkage \(\psi_f\) and the synchronous inductance \(L_s\) could be calibrated from (9) and (11). The control parameters \(K_{pv}, K_{iw}\) of the speed loop could be adjusted by

\[
\begin{align*}
K_{pv} &= \frac{\beta M \tau}{1.5 \pi P v \psi_f} \\
K_{iw} &= \beta K_{pv}
\end{align*}
\]

(12)

where \(\beta\) is the expected bandwidth of the speed loop, \(M\) is the mass of the PM mover, \(P\) is the pole of pairs.

For the current loop of the segmented PMSLM, the internal model control is used for the parameter adjustment, there are

\[
\begin{align*}
K_{id} &= \alpha L_d \\
K_{iq} &= \alpha L_q \\
K_{pv} &= \alpha R_s \\
K_{iw} &= \alpha R_q
\end{align*}
\]

(13)

where \(\alpha\) is the bandwidth of the current loop, and it could be achieved by

\[
\alpha = \frac{2 \pi}{f} = \max \left\{ \frac{2 \pi R}{L_d}, \frac{2 \pi R}{L_q} \right\}
\]

(14)

According to (12), (13) and (14), the control parameters are proportional to the PM flux linkage \(\psi_f\) and the synchronous inductance \(L_s\). According to the calibration values of coupling area between the PM mover and the stator with driving coils, the ratio between the updating value and the previous value of EM parameters could be calculated. When the PM mover enters a new stator with driving coils again, the control parameters could be updated according to this ratio to enhance the control performance.

\[\text{FIGURE 5. The diagram of the sensorless control method.}\]

\[\text{FIGURE 6. The diagram of the sensorless control method.}\]

\[\text{FIGURE 7. The diagram of the sensorless control method.}\]

\[\text{FIGURE 8. The diagram of the sensorless control method.}\]

\[\text{FIGURE 9. The diagram of the sensorless control method.}\]
of estimated stator flux linkage, the orthogonality would be affected immediately. In the meanwhile, a regulator could generate the compensation term of the orthogonality, and then it is fed back to the flux linkage estimation module. Consequently, the problems caused by the DC offset and the initial value could be solved.

In order to keep the stability of designed system, the model reference adaptive algorithm with the back-EMF integration is used to estimate the speed and position of the PM motor. The principle diagram is shown in FIGURE 7.

The flux linkage equations of the segmented PMLSM are

$$\begin{align*}
\dot{\psi}_a &= L_a \ddot{i}_a + \psi_f \cos \theta_r - |\psi_s| \cos \theta_r \\
\dot{\psi}_b &= L_b \ddot{i}_b + \psi_f \sin \theta_r = |\psi_s| \sin \theta_r
\end{align*}$$

(16)

The control currents could be expressed into

$$\begin{align*}
i_a &= \frac{\psi_a}{L_a} - \frac{\psi_f}{L_a} \cos \theta_r = \frac{|\psi_s|}{L_a} \cos \theta_r - \frac{\psi_f}{L_a} \cos \theta_r \\
i_b &= \frac{\psi_b}{L_b} - \frac{\psi_f}{L_b} \sin \theta_r = \frac{|\psi_s|}{L_b} \sin \theta_r - \frac{\psi_f}{L_b} \sin \theta_r
\end{align*}$$

(17)

According to (16) and (17), there are

$$\begin{align*}
\frac{d\ddot{i}_a}{dt} &= -\frac{L_b}{L_a} \dddot{i}_b = -\frac{L_b}{L_a} \pi \dot{\psi}_b \\
\frac{d\ddot{i}_b}{dt} &= \frac{L_a}{L_b} \dddot{i}_a = \frac{L_a}{L_b} \pi \dot{\psi}_a
\end{align*}$$

(18)

The state-space function could be written into

$$\begin{bmatrix}
\frac{d\ddot{i}_a}{dt} \\
\frac{d\ddot{i}_b}{dt}
\end{bmatrix} = A \cdot \begin{bmatrix} \ddot{i}_a \\ \ddot{i}_b \end{bmatrix}$$

(19)

And

$$A = \begin{bmatrix} 0 & -\frac{L_b}{L_a} \pi \\ \frac{L_a}{L_b} \pi & 0 \end{bmatrix}$$

(20)

According to the model reference adaptive principle, (18) could be used as an adjustable model with the adjustable parameter $\psi$, and the nominal model of the segmented PMLSM is used as the reference model.

The estimated form of (18) could be written into

$$\begin{align*}
\frac{d\hat{\ddot{i}}_a}{dt} &= -\frac{L_b}{L_a} \pi \dot{\hat{\psi}}_b \\
\frac{d\hat{\ddot{i}}_b}{dt} &= \frac{L_a}{L_b} \pi \dot{\hat{\psi}}_a
\end{align*}$$

(21)

The generalized error is defined as

$$e = i - \hat{i}$$

(22)

According to (18) and (21), the differential form of the error equation could be expressed as

$$\begin{bmatrix}
\frac{de_a}{dt} \\
\frac{de_b}{dt}
\end{bmatrix} = A \cdot \begin{bmatrix} e_a \\ e_b \end{bmatrix} - W (v - \hat{\psi}) J \begin{bmatrix} \hat{i}_a \\ \hat{i}_b \end{bmatrix}$$

(23)

There are

$$\begin{align*}
e_a &= i_a - \hat{i}_a \\
e_b &= i_b - \hat{i}_b
\end{align*}$$

(24)

And

$$W = (v - \hat{\psi}) J \begin{bmatrix} \hat{i}_a \\ \hat{i}_b \end{bmatrix}$$

(25)

It also could be expressed as the following form

$$\frac{de}{dt} = A \cdot e - W$$

(26)

To satisfy the Popov hyper-stable theory [31], the following two conditions must be satisfied.

1) The transfer matrix $H(s) = (sI - A_x)^{-1}$ must be a strictly positive definite matrix.

2) Given that $\gamma_0$ is a finite positive number, there is

$$\eta(0, t_1) = \int_0^t V^T W dt > -\gamma_0^2, \quad \forall t_1 \geq 0$$

(27)

According to (20), $A_x$ satisfies the first condition. To satisfy the second condition, $\hat{\psi}$ is defined as

$$\hat{\psi} = \int_0^t \Phi_1 (e, \tau, t) d\tau + \Phi_2 (e, \tau) + \hat{\psi}(0)$$

(28)

Then $\eta(0, t_1)$ could be written as

$$\eta(0, t_1) = \int_0^t e^T \left[ \int_0^t \Phi_1 (e, \tau, t) d\tau + \Phi_2 (e, \tau) + \hat{\psi}(0) - v \right] \hat{f} dt$$

(29)
For arbitrary functions, there is the following inequality

\[ \eta(0, t) = \int_0^{t_1} e^T \Phi_2(e, t) \hat{f} dt = \eta_1(0, t_1) + \eta_2(0, t_1) \]  

(29)

For arbitrary functions, there is the following inequality

\[ \eta(0, t_1) = \int_0^{t_1} k f(t) f'(t) dt = \frac{1}{2} k \left[ f^2(t_1) - f^2(0) \right] > \frac{1}{2} k f^2(0) = -\gamma_0^2 \]  

(30)

There are assumptions as following

\[ \begin{cases} f'(t) = e^T J \dot{i} \\ k f(t) = \int_0^t \Phi_1(e, \tau, t) d\tau + \hat{\nu}(0) - v \end{cases} \]  

(31)

After the derivation, we could obtain

\[ \begin{cases} \Phi_1(e, \tau, t) = K_i e^T J \dot{i}, & \text{if } K_i > 0 \\ \Phi_2(e, t) = K_p e^T J \dot{i}, & \text{if } K_p > 0 \end{cases} \]  

(32)

where \( K_i \) and \( K_p \) are correlation coefficients.

There is

\[ \eta_2(0, t_1) = K_p \int_0^{t_1} \left( e^T J \dot{i} \right)^2 dt \geq 0 \]  

(33)

Therefore, the second condition is met by

\[ \eta(0, t_1) = \eta_1(0, t_1) + \eta_2(0, t_1) \geq -\gamma_0^2 \]  

(34)

According to (28) and (32), the adaptive law of speed could be described as

\[ \begin{align*} \dot{\nu} & = K_p e^T J \dot{i} + \int_0^t K_i e^T J \dot{i} d\tau + \hat{\nu}(0) \\ & = K_p \left[ \frac{L_\alpha}{L_\beta} \tau i_\alpha (i_\beta - \hat{i}_\beta) - \frac{L_\beta}{L_\alpha} \tau i_\beta (i_\alpha - \hat{i}_\alpha) \right] \\ & + \int_0^t \left[ \frac{L_\alpha}{L_\beta} \tau \hat{i}_\alpha (i_\beta - \hat{i}_\beta) - \frac{L_\beta}{L_\alpha} \tau \hat{i}_\beta (i_\alpha - \hat{i}_\alpha) \right] d\tau + \hat{\nu}(0) \end{align*} \]  

(35)

The estimated position could be achieved by integrating the speed of the PM mover

\[ \hat{x} = \int_0^t \dot{\nu} d\tau \]  

(36)

The control performance of the segmented PMLSM is improved by combining the parameters calibration with the improved back EMF integration method.

**IV. SIMULATION AND EXPERIMENTS**

**A. SIMULATION RESULTS**

In this part, simulations are conducted to verify the feasibility of the sensorless control with the parameter calibration, and the parameters of the segmented PMLSM used in simulations are listed in TABLE 1.

| Symbol | Parameter | Value |
|--------|-----------|-------|
| \( P_e \) | Pole of pairs | 3 |
| \( M \) | Mass of PM mover | 5kg |
| \( B \) | Viscous friction factor | 1.6 |
| \( x_m \) | Length of PM mover | 140mm |
| \( \tau \) | Polar pitch | 20mm |
| \( \dot{i}_f \) | Equivalent current of PM | 11A |
| \( L_{ir} \) | Leakage inductance | 2.8mH |
| \( \psi_r \) | PM flux linkage | 0.02Wb |
| \( L_s \) | Synchronous inductance | 4.6mH |
| \( \psi \) | Speed of PM mover | 2m/s |
| \( L_s \) | Length of each primary stator | 400mm |
| \( L_t \) | Distance of adjacent segments | 100mm |

**FIGURE 8.** Speed response curves of the PM mover with different control models. (a) \( \psi_f = 0.01Wb \) and \( L_s = 2.8mH \), (b) \( \psi_f = 0.05Wb \) and \( L_s = 7.8mH \).
speed curves of three different control models are illustrated in FIGURE 8(b). The overshoot of the perturbation model without the parameter calibration reaches 15.2% and the setting time is 0.06s, but the perturbation model with the parameter calibration has no obvious overshoot and its setting time is 0.03s. Therefore, the control performances of simulation model with parameter calibration are better than that without parameter calibration by reducing the overshoot and the settling time, so it is necessary to calibrate the EM parameters when the PM mover runs on different stators during the switch process.

2) SIMULATION OF SENSORLESS CONTROL

In order to verify the effectiveness of the improved integrator used in the sensorless control, a DC offset with 0.05V is added to the back-EMF voltages $e_\alpha$ and $e_\beta$. The pure integrator, the low-pass filter and the improved integrator are respectively applied to estimate the stator flux linkages $\psi_\alpha$ and $\psi_\beta$, and the trajectories of the stator flux linkage are plotted in FIGURE 9. The reference flux linkage is a perfect cycle in FIGURE 9(a), and its radius is 0.01Wb. For the flux linkage with the pure integrator as shown in FIGURE 9(b), the deflection from reference flux linkage reaches to 0.015Wb. As illustrated in FIGURE 9(c), the flux linkage with the low-pass filter exceeds the radius of the reference flux linkage. Finally, the flux linkages with an improved integrator are close to the reference flux linkages in FIGURE 9(d). Therefore, the improved integrator could effectively restrain the DC offset and reduce the phase shift of flux linkage.

In addition, the position estimation accuracy of the improved integrator is also testified. The actual position of the PM mover is illuminated in FIGURE 10(a), and the estimated position of the PM mover applying the improved integrator is plotted in FIGURE 10(b). The error between the actual position and the estimated position is shown in FIGURE 10(c), and the estimation error approaches to a constant range within 0.002m. Therefore, the improved integrator used in the sensorless control of the segmented PMLSM could precisely track the actual position of the PM mover.

Furthermore, an improved integrator based on the model reference adaptive principle is used to improve the robustness of the segmented PMLSM. The phase of the back EMF voltage could be estimated by the model reference adaptive law, and the phase comparisons of the back EMF voltages with different control models are plotted in FIGURE 11 when the load disturbance is added on the PM mover at 0.04s and removed at 0.16s. The red solid line is the actual phase of the back EMF voltage, and the blue dotted line presents the estimated phase of the back EMF voltage. As shown in FIGURE 11(a), for the normal integration method used to estimate the back EMF voltage, there is an obvious phase jump when the load disturbance is imposed on the PM mover. For the improved integration method based on the model reference adaptive principle, the estimated phase of the back EMF voltage could accurately track the
The experimental setup of the segmented PMLSM.

The improved integration method based on the model reference adaptive principle has strong anti-disturbance when the PM mover is suffered from disturbance.

B. EXPERIMENT RESULTS

Experiments are conducted to further prove the feasibility of the proposed control model for the segmented PMLSM. The experimental setup is shown in FIGURE 12, and it has two parts including the segmented PMLSM and the control system. For the control system, a digital signal processor (DSP) board (TMS320F28377s) is used as the main control unit (MCU) to realize the real-time control of the segmented PMLSM based on the position/speed signal captured by the magnetic rulers, and the control frequency is 10kHz. The driver board DRV8301 is used to drive the stator coils of the segmented PMSLM. During the experiment, the PM mover is driven to the reference speed using the sensorless control during the drive process, and the parameter calibration is conducted during the switch process to regulate the control parameters.

1) EXPERIMENT OF PARAMETERS CALIBRATION

Firstly, the effectiveness of the parameter calibration is verified through calibrating the back EMF voltage, the PM flux linkage and the synchronous inductance in the experiment. The calibrated results of the EM parameters are shown in FIGURE 13 when the PM mover works at the switch process from the rail without driving coils into the stator with driving coils. The nominal value of the PM flux linkage $\psi_f = 0.02 \text{Wb}$ and the synchronous inductance $L_s = 4 \text{mH}$, respectively. As shown in FIGURE 13, the calibrated results of the EM parameters converge to the nominal values at 0.15s. The error between the calibrated result and the nominal value of the PM flux linkage is 0.001Wb in FIGURE 13(b), and the error of the synchronous inductance is 0.1mH as shown in FIGURE 13(c). Therefore, the parameter calibration could be used in the sensorless control of the segmented PMLSM to improve the estimation precision of the position and speed during the switch process.

2) EXPERIMENT OF SENSORLESS CONTROL

Moreover, as illustrated in FIGURE 14, the phases of the back EMF voltages are measured and compared in the experiment. For the phase of the back EMF voltage estimated by the normal integration method in FIGURE 14(a), the error between the actual and estimated phases of the back EMF voltage reaches to 1.5rad, so there is obvious phase shift by using the normal integrator in the sensorless control. In addition, the phase of the back EMF voltage estimated by the improved integrator with the parameter calibration is plotted in FIGURE 14(b), the error between the actual phase and the estimated phase is declined from 1.5rad to 0.07rad. Therefore, the improved integration in the sensorless control of the segmented PMLSM has better performance on estimating the back EMF voltage, and then control precision of the segmented PMLSM would be improved.

The speed curve of the PM mover is shown in FIGURE 15. The speed of the PM mover is 1.772m/s when it starts to enter the stator with driving coils from the rail without driving coils, and then the speed of the PM mover is accelerated to the rate...
speed (2m/s). At $t = 0.45s$, the actual speed of the PM mover converges to the rate value, and the error between the actual and the rate speed is restrained to 0.04m/s. Those results satisfy the requirements of the segmented PMLSM on speed convergence and stability. Furthermore, the speed curve of the PM mover during three motion processes is plotted in FIGURE 16, there are obvious oscillations during the switch process and speed reduction during the slide process. For the speed curve of the PM mover without the parameter calibration shown by the red line, the speed of the PM mover would be reduced to 1.82m/s. The speed curve of the PM mover with the parameter calibration is marked by the blue line, and the speed is only declined to 1.9m/s. Therefore, the sensorless control with the parameter calibration has better dynamic performance on the speed control of the segmented PMLSM.

V. CONCLUSION
In this article, the sensorless control model with the parameter calibration is of great significance for the application of the segmented PMLSM in the long-distance auto-transportation system. The PM mover and stators of the segmented PMLSM are not fixedly paired, so the performance of the sensorless control would be affected when the PM mover slides into a new stator with driving coils during the switch process. Thus, the parameter calibration is applied to get the accurate EM parameters during the switch process of the PM mover. An model reference adaptive integrator could improve the precision of the sensorless control and the anti-disturbance performance. This proposed control model could be applied to the control engineering of PMLSM with segmented stators.

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FIGURE 15. (a) The speed curve of the PM mover, (b) the error between the reference speed and the actual speed.

FIGURE 16. The speed curve of the PM mover during three motion processes.
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**TONG WEN** was born in Hunan, in 1983. He received the B.S. and Ph.D. degrees from the Beijing University of Aeronautics and Astronautics, Beijing, China, in 2005 and 2012, respectively. He is currently a Lecturer and a master’s Tutor with the School of Instrumentation and Optoelectronic Engineering, Beihang University. His current research interests include linear motor control, control of the active magnetic bearing, and magnetic suspension inertial stabilization platform used in the aviation remote sensing systems.

**ZHONGYI WANG** was born in Shandong. She received the B.S. degree from Guangxi University, Nanning, China, in 2018. She is currently pursuing the degree with the School of Instrumentation and Optoelectronic Engineering, Beihang University, Beijing, China. Her research interest includes motor control.

**BIAO XIANG** was born in 1987. He received the B.S. degree in physical and mechanical engineering from Xiamen University, Xiamen, China, and the M.S. degree in instrumentation science and opto-electronics engineering from Beihang University (Beijing University of Aeronautics and Astronautics), Beijing, China. He is currently pursuing the Ph.D. degree in vibration analysis and control with the Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong. His research interests include vibration measurement analysis, active vibration control, and control of magnetically suspended rotational machines.

**BANGCHENG HAN** (Member, IEEE) was born in 1974. He received the M.S. degree in mechanical design and theory from Jilin University, Changchun, China, in 2001, and the Ph.D. degree in mechanical manufacture and automation from the Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, in 2004. He is currently a Professor with the School of Instrumentation and Optoelectronic Engineering, Beihang University, Beijing, China. His research interests include mechatronics, magnetic suspension technology, and attitude control actuator of spacecraft.

**HAI TaoLI** (Member, IEEE) was born in Shandong, in 1979. He received the B.S. and M.S degrees from Shandong University, Jinan, China, in 2002 and 2005, respectively, and the Ph.D. degree from the Beijing University of Aeronautics and Astronautics, Beijing, China, in 2009. He is currently an Associate Professor with the School of Instrumentation and Optoelectronic Engineering, Beihang University. He is also with the Fundamental Science on Novel Inertial Instrument and Navigation System Technology Laboratory, China. His main research interest includes magnetically suspended control moment gyro (MSCMG) and its nonlinear control.