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Initial Pole Position Estimation of Surface PM-LSM

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ABSTRACT

The elimination of a pole sensor is desirable due to the low-cost requirement, the compactness, and the applied drives. This paper proposes the algorithm for the initial pole-position estimation of a surface permanent magnet linear synchronous motor (PM-LSM), which is carried out under the closed loop control without a pole sensor and is insensitive to the motor parameters. This algorithm is based on the principle that the initial pole position (IPP) is estimated by the trigonometric function of the two reference currents. The effectiveness of the proposed algorithm is confirmed by testing a surface PM-LSM with large disturbance, which result shows that IPP is well estimated within a satisfied moving-distance and a shorter estimation taken-time even if large disturbance such as cogging and friction is existed.

Key Words : SPMSM, IPMSM, surface PM-LSM, initial pole position, pole sensorless, linear motor

1. Introduction

The permanent magnet synchronous motor (PMSM) has been widely applied to the industrial and servo-drive fields. It has robust structure and it is maintenance-free.

Furthermore, with appropriate control strategy, it can result in significant energy-savings and high performances. However, it requires the precise initial-pole-position information (typically obtained by means of a pole sensor) for a smooth start-up and a precise servo-drives. Often it is prohibitive to install a pole sensor on the motor shaft due to the compactness and low-cost requirements. In particular, the permanent magnet linear synchronous motor (PM-LSM) drives would require an expensive pole-sensor and often be exposed to heat, dust, electric noise, mechanical vibration, etc. such that the position sensor signals get distorted. On the other hand, if the initial pole position (IPP) cannot be precisely known, the performances of a motor itself may not be obtained. The motor may produce less torque or it may become unstable. Moreover, during start-up it may rotate in the wrong direction.

Recently, the research concerning IPP estimation of PMSM has been focused and progressed[1]-[4]. But most of researches were on the pole position estimation of an interior permanent magnet synchronous motor (IPMSM), which can be easily calculated by the impedance ratio (Zq/Zd). And only a few papers were focused on the IPP estimation of a surface permanent magnet synchronous motor (SPMSM), which cannot be easily calculated without the information of enough EMF and can be calculated by using the magnetic saturation. However, the estimation method using the magnetic saturation of SPMSM, which has lately considerable attention, is

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subject to the types of a stator core[4][5]. The above-mentioned methods of IPP estimation are mostly carried out under open-loop control or torque control (thrust control in case of a linear motor). These methods under the open-loop control or the thrust control are not effective to estimate the IPP, in the existence of disturbance such as cogging and friction, because the estimation accuracy and the moving distance can be easily varied in the disturbance.

Authors propose the estimation algorithm for the initial pole position of a surface permanent magnet linear synchronous motor (surface PM-LSM), which is carried out under the closed-loop control[6]. The algorithm is based on the principle that IPP is calculated by the trigonometric function ($\tan^{-1}$) of two reference currents. The effectiveness of the proposed algorithm will be confirmed by the experiments, in which the surface PM-LSM with large disturbance will be tested.

In the section 2, the principle of the proposed initial pole position estimation will be described, and the experiment results will be discussed in the section 3. Finally, the paper will be concluded as the section 4.

2. Principle of Initial Pole Position Estimation

In Fig. 1, two *d-q* reference frames are considered as a control side's *d-q* reference frame and a motor side's *d-q* reference frame. For example, the actual IPP of a linear motor may be placed on a temporary control side's *d-q* reference frame and is directed toward the *d* coordinate axis of a motor side's *d-q* reference frame. The actual IPP shown in this figure is deviated from a temporary control side's *d-q* reference frame, the deviated angle of which is defined as the deviated IPP (Θ err). To detect the actual IPP, a special sensor (pole sensor) is generally necessary. But the IPP can be simply calculated by information of a feedback speed and two reference currents.

Under constant flux (Φ), some thrust (Te) is necessary for a linear motor to be moved as the same reference speed regardless of any deviated IPP, which is the principle of the proposed initial pole position estimation. To estimate the IPP under the speed-control systems, two reference currents including the necessary thrust are informed. One ($I1^*_{data}$) of two reference currents is obtained from the speed controller under no-shift position mode (Θ shift = 0deg) and the other ($I2^*_{data}$) is obtained under shift position mode (Θ shift = 90deg). Both of two reference currents may include a thrust component current (effective current) and a flux component current (ineffective current), whose quantities are respectively determined according to the trigonometric function of any deviated IPP, as show in Fig. 8. In Fig. 8, the loss thrust (Tloss) is caused by the ineffective current and the generated thrust (Te) is caused by the effective current.

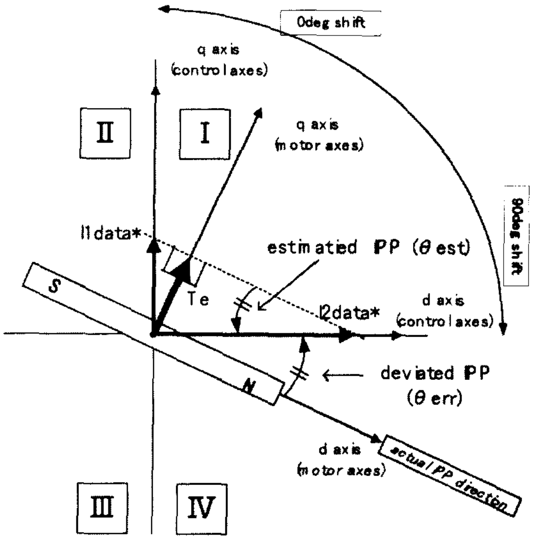


Fig. 1. Relation between Deviated IPP and Estimated IPP.

The position information (Θ ref) into current controller of Fig. 1 is adjusted by (1), which has the function for selecting the interval modes (1st ref. speed interval and 2nd ref. speed interval) of Fig. 3.

$$\Theta\,\mathrm{ref} \leftarrow \Theta\,\mathrm{fb} - \Theta\,\mathrm{shift} + \Theta\,\mathrm{cmp} \qquad (1)$$

where Θ ref is a position, Θ fb is a feedback position (relative position), Θ shift is the no-shift and shift position mode (0deg or 90deg), and Θ cmp is a estimated IPP (=Θ offset +Θ est) and 0deg during estimation.

Speed is obtained through the motion equation of (2).

$$\omega = F(\mathrm{Te}, \mathrm{TL}, \mathrm{D}) \qquad (2)$$

where F is a function, Te is a generated thrust (actual thrust), TL is load thrust, and ω is a speed.

To get the same feedback speed as the reference speed, the necessary thrust under no-shift position mode is obtained from (3) and the necessary thrust under shift position mode is obtained from (4).

$$\mathrm{Te} = \mathrm{K_T} \times \mathrm{I1}^*_{\mathrm{data}} \times \cos(\Theta\ \mathrm{err}) \qquad (3)$$

$$\begin{aligned}\mathrm{Te} &= \mathrm{K_T} \times \mathrm{I2}^*_{\mathrm{data}} \times \cos(\Theta\ \mathrm{err} - 90\mathrm{deg}) \\ &= \mathrm{K_T} \times \mathrm{I2}^*_{\mathrm{data}} \times \sin(\Theta\ \mathrm{err}) \qquad (4)\end{aligned}$$

where $\mathrm{K_T}$ is a thrust constant, $\mathrm{I1}^*_{\mathrm{data}}$ is the 1st reference current, and $\mathrm{I2}^*_{\mathrm{data}}$ is the 2nd reference current.

Because each necessary thrust of both no-shift and shift position modes is the same, (3) and (4) can be rewritten as (5).

$$\mathrm{K_T} \times \mathrm{I1}^*_{\mathrm{data}} \times \cos(\Theta\ \mathrm{err}) = \mathrm{K_T} \times \mathrm{I2}^*_{\mathrm{data}} \times \sin(\Theta\ \mathrm{err}) \qquad (5)$$

From the relation of (5), the deviated IPP of (6) is obtained. Therefore, the actual IPP of a linear motor can be estimated by (6).

$$\theta_{est} = \theta_{err} = \tan^{-1}\left[\frac{I^*_{1data}}{I^*_{2data}}\right] \qquad (6)$$

As previously described in this chapter, even if the IPP is located on any point of the 4th quadrant (270deg ~ 360deg) shown in Fig. 1, the same amplitude of actual thrust is necessary for a linear motor to be moved according to the same reference speed. Therefore, the deviated IPP can be calculated by (6).

Consider the cases that the deviated IPP is 0deg, 45deg, and 90deg, respectively.

In the case 1 (Θ err=0deg), the necessary thrust can be obtained only from no-shift position mode and the obtained reference current ($\mathrm{I1}^*_{\mathrm{data}}$) and the necessary thrust are the same. The reference current obtained from shift position mode includes only an ineffective current.

In the case 2 (Θ err=45deg), the necessary thrust can be obtained from no-shift position mode and shift position modes. The obtained two reference currents include an effective current and an ineffective current, respectively.

In the case 3 (Θ err=90deg), the reference current obtained from no-shift position mode includes only an ineffective current. The necessary thrust can be obtained only from shift position mode and the obtained reference current ($\mathrm{I2}^*_{\mathrm{data}}$) and the necessary thrust are the same.

The above examples are shown in Fig. 2 and are summarized in Table 1.

Table 1 Relation between 1st & 2nd Ref. Current by Deviated IPP.

deviated IPP	0deg	45deg	90deg
actual speed	○speed	○speed	×speed
actual thrust	○thrust	○thrust	×thrust
1st ref. current	pure	mix	∞
2nd ref. current	∞	mix	pure

*○speed and ○thrust : good response speed and thrust

*×speed and ×thrust : zero speed and thrust

*pure means only actual thrust (effective current) is included.

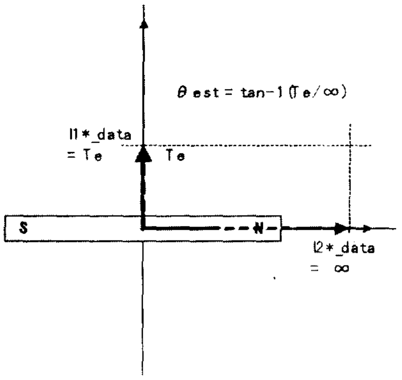
*mix means effective current and ineffective current are included.

The procedures of the proposed algorithm are described as follows and its flowchart is also shown in Fig. 3. The proposed method in Fig. 1 is referred to the flowchart.

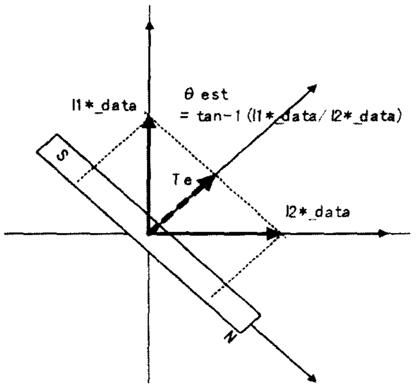
STEP 1 initialization of variables : 1
STEP 2 reference speed generation and PI control : 2, 3
STEP 3 interval mode selection : 4, 51 and 61
STEP 4 data accumulation & storage of $\mathrm{I1}^*_{\mathrm{data}}$: 53, 54
STEP 5 data accumulation & storage of $\mathrm{I2}^*_{\mathrm{data}}$: 63, 64

STEP 6 end of ref. speed total interval : 7
STEP 7 data $I1^{*}_{call}$, $I2^{*}_{call}$ calling from memory : 8
STEP 8 calculation of IPP : 9, 10

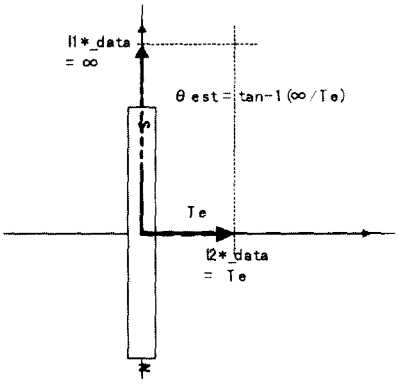
<notice> the above-mentioned number coincides with the label number inside Fig. 3.



(a) case 1 (θ err = 0deg)



(b) case 2 (θ err = 45deg)



(c) case 3 (θ err = 90deg)

Fig. 2. Relation between 1st and 2nd reference currents by deviated IPP.

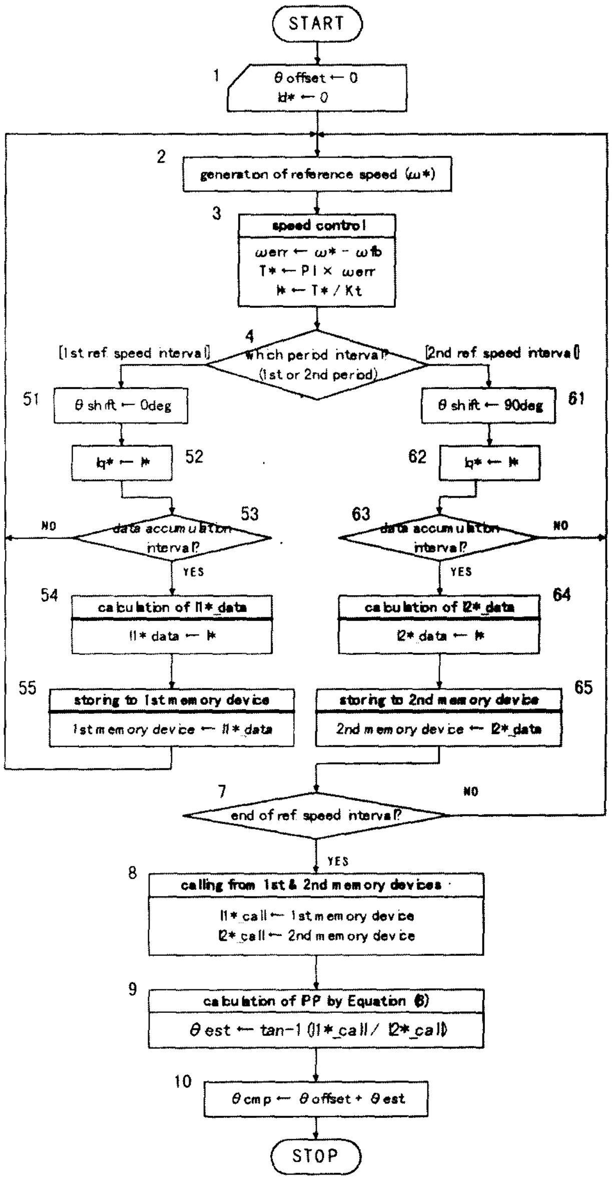


Fig. 3. Overall Flowchart of Proposed Method.

3. Experiments

3.1 Reference Speed Pattern

A reference speed pattern is considered for the proposed method, which is carried out by the speed control. And the information about 1st reference current and 2nd reference current can be easily obtained from the closed-loop system. The reference speed pattern of trapezoid waveform shown in Fig. 4 is freely adjusted by the following parameters ; 1) pause interval time, 2) accelerating / decelerating interval time, 3) constant speed interval time, and 4) maximum speed.

Accordingly, it can be also redesigned such as a) rectangle, b) trapezoid, and c) zero-speed waveform.

In the reference speed pattern of the proposed method, the reference speed total interval is consisted of the 1st ref. speed interval and the 2nd ref. speed interval. And the reference speed ω^* is designed for a motor to return to the starting position after each reference speed interval.

3.2 System Configurations

The test motor is a surface permanent magnet linear synchronous motor, which specifications are listed in Table 2.

Table 2 Spec. of Moving Coil Type PM-LSM.

item	unit	value
rated output	W	3000
rated thrust	N	2000
rated speed	m/s	1.5
rated current	Arms	20
pole pitch	mm	45
linear scale resolution	μ m	1
moving mass	kg	56

And the resolution of the linear scale is 1μ m, the pole sensor is not installed on the surface PM-LSM, and the pole pitch of a motor is 45mm.

The actual IPP of the test motor is measured by the mechanical structure, and is monitored by the measuring instrument of displacement, which is shown in Fig. 5.

By adding 120kg load mass to the moving mass, the load condition is divided as no-load and full-load. Fig. 5 shows the overall configurations of the experimental system for verifying the effectiveness of the proposed algorithm.

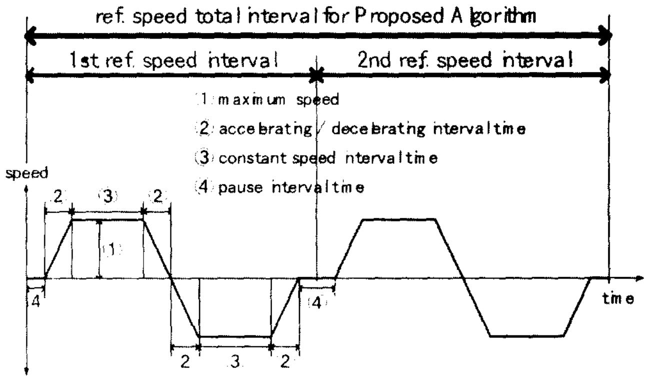


Fig. 4. Reference Speed Pattern (Trapezoid Waveform).

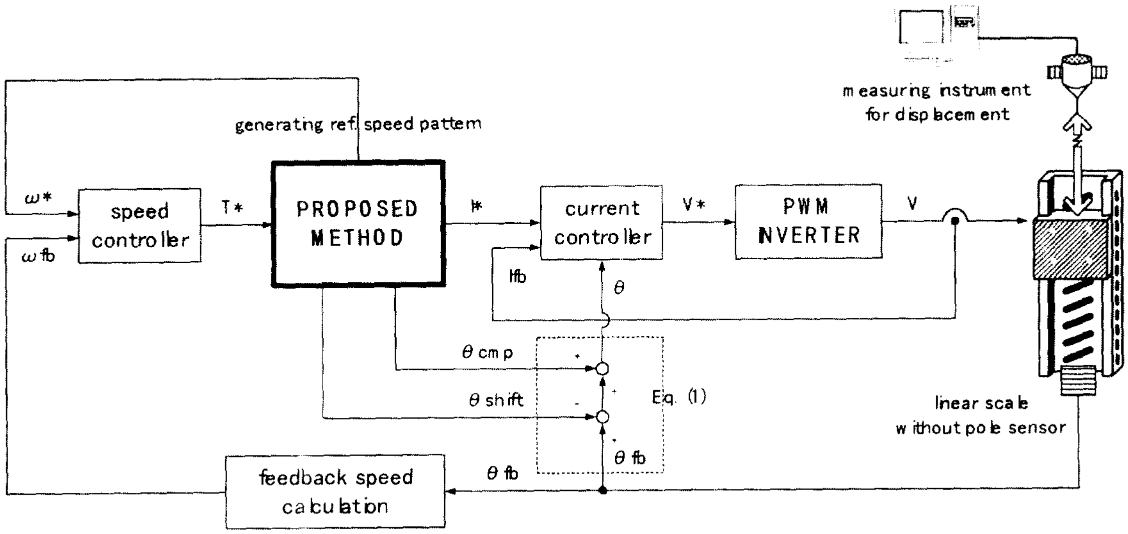


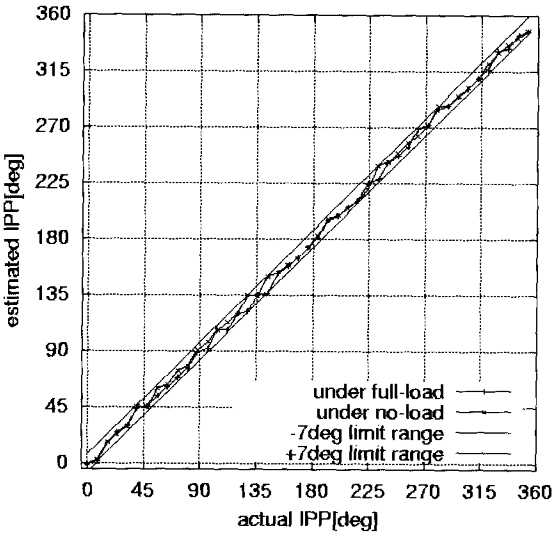
Fig. 5. Overall Block Diagram for Proposed Method in Experiments.

3.3 Estimation Results

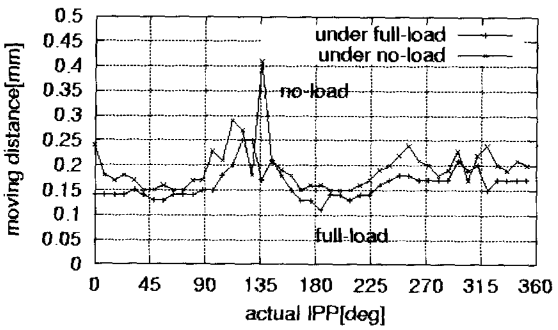
Table 3 Experimental Results under Load Condition.

evaluation item	unit	full-load	no-load
estimation accuracy error	deg	2.64	2.51
	mm	0.33	0.31
moving distance during estimation	deg	1.28	1.52
	mm	0.16	0.19
estimation time*	sec	2.04	2.34

<notice> : meaning with * is time taken during estimation

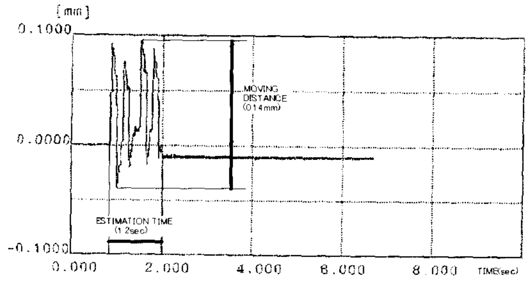


(a) Relation between Actual and Estimated IPP

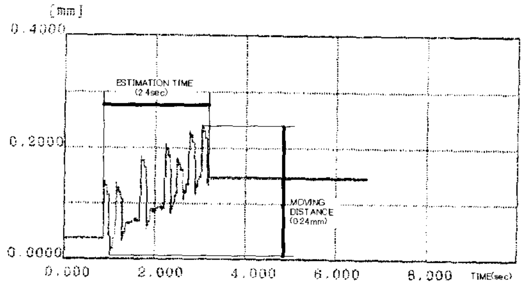


(b) Moving Distance according to Actual IPP

Fig. 6. Experimental Results under Full-Load and No-Load Conditions.



(a) Full-Load



(b) No-Load

Fig. 7. Displacement Transition during estimation at the IPP of 0mm (0deg).

In the overall experimental results of 0mm ~ 45mm (equivalent to 0deg ~ 360deg) range, the moving distance under full-load and no-load conditions is 0.16mm and 0.19mm, respectively. And also the estimation-accuracy-error (EAE) is 0.33mm (2.64deg) and 0.31mm (2.51deg), respectively.

The experimental results are summarized in Table 3. Fig. 6-(a) shows the relation between actual IPP and estimated IPP, and Fig. 6-(b) shows the moving distance according to the actual IPP. The EAE of 1mm (8deg) is equal to the thrust loss of about 1%, which can be enough ignored. The thrust loss is calculated by (3). The relation between the actual thrust and the reference thrust according to the error of IPP can be expressed by (4) and is shown in Fig. 8.

$$T_{loss} = T^{*} \times \left[1 - \cos(\theta_{err})\right] \quad (3)$$

$$T_{e} = T^{*} \times \cos(\theta_{err}) \quad (4)$$

The actual IPP of the test motor is set to the position of 0mm (equivalent to 0deg in a rotating motor) as an instance. Fig. 7 shows the displacement waveform, measured by the measuring instrument of displacement, during the estimation.

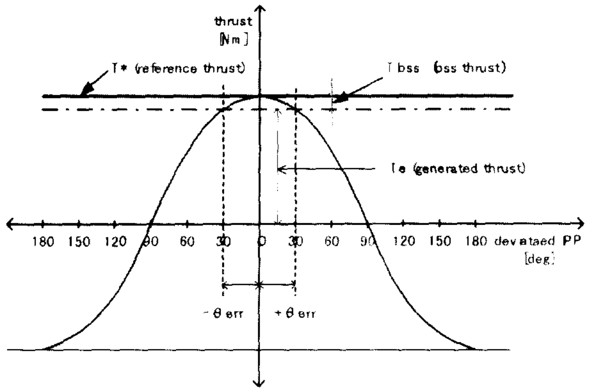


Fig. 8. Relation between Generated & Ref. Thrust.

4. Conclusions

In this paper, the algorithm for the IPP estimation of a surface PM-LSM was proposed and its effectiveness was confirmed by experiments. The IPP can be easily and well estimated by the calculation (trigonometric function) of two reference currents, which are obtained under the closed-loop control.

The experimental results (0mm~45mm range by 1mm step : equivalent to 0deg ~ 360deg range by 8deg step in a rotating motor) about a surface PM-LSM, which has large disturbance, are summarized as follows.

- <u>**Results under Full-Load Condition**</u>
  - * Estimation-accuracy-error is 0.33mm (2.64deg)
  - * Moving-distance during estimation is less than 0.25mm (2.0deg)
- <u>**Results under No-Load Condition**</u>
  - * Estimation-accuracy-error is 0.31mm (2.51deg)
  - * Moving-distance during estimation is less than 0.29mm (2.3deg)

According to the experimental results, the IPP can be well estimated within a small estimation-accuracy-error of 0.875mm (pole pitch of linear motor = 45mm), equal to 7deg in a rotating motor, even if a large disturbance of friction and cogging is existed in a motor.

Finally, the proposed algorithm, applied to the surface PM-LSM in the paper, can be also applied to the SPMSM (a rotating motor) and the good result may be obtained. Their results will be reported in soon.

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Appendices

d, *q* : subscripts of *d* axis and *q* axis
fb, est : subscripts of feedback and estimation
data, call : subscripts of data for estimating IPP
* : subscript of reference
V^* : reference voltage
θ err, θ est : deviated IPP and estimated IPP
θ offset, initialized position (0deg)
θ cmp : compensated position
θ fb : feedback relative position
θ shift : no-shift and shift position (0deg or 90deg)
ω_{fb}, ω^* : feedback speed and reference speed

T_e, T^* : actual thrust and reference thrust
TL : load thrust
T_{loss} : thrust loss
Φ : actual flux
D : damping factor
K_T : thrust constant
$I1^*_{data}$, $I2^*_{data}$: 1st and 2nd ref. current ($=T^* / K_T$)
deg : electrical degree (°)
IPP : initial pole position
EAE : estimation-accuracy-error

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