Design and implementation of a cost-effective position control system for an ironless linear motor

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Abstract: Due to attractive features including a high reliability, low maintenance, and a low cost, stepping motors with an open-loop drive have found wide application in motion control systems. However, the performance of a stepping motor that is under open-loop control deteriorates when either the frequency of the input pulse train is increased or an external load is unexpectedly added. A high-performance, cost-effective direct-drive position-control system with an ironless linear permanent-magnet synchronous motor (ILPMSM) is proposed to overcome these difficulties. Instead of using a multi-loop cascaded-feedback control structure, the position is controlled by regulating the orientation and magnitude of the excited space current vector of the moving coil of the ILPMSM. Also, the effect of the dead time on the positioning accuracy is investigated and a cost-effective position-error compensation approach in the $d$-$q$ plane is introduced. Compared with general hybrid stepping motors several advantages are observed when using the proposed control strategy, including: (i) the resolution of the stepping increment and the holding force are software programmable; and (ii) limited losing steps can be automatically eliminated during the travelling process. A high-performance digital signal processor is used to implement the proposed control algorithm. Experimental results verify that the proposed approach exhibits a satisfactory performance.

1 Introduction

Rapid developments in power electronics, microelectronics and high-performance permanent magnets in the last two decades have lead to the development of DC brushed linear motors, linear induction motors, linear permanent-magnet synchronous motors (LPMSMs) and linear stepping motors for application to a variety of commercial situations [1–5]. A linear motor can be thought of in terms of the stator and rotor of a general rotary motor being cut along the radial plane and then stretched out. The use of linear motors means that there is no need to convert rotary motions into linear motions (known as ‘direct drive’) and thus several benefits such as being backlash free, a high feedrate (5–10 m/s), high accelerations (15–20 m/s²), a smaller and compact space, and unlimited strokes can be achieved. Depending on the type of feedback sensors used in the systems, the position of accuracy and repeatability for generally available commercial products is now 1–3 μm [1, 2]. Because of their dynamic performance, ease of installation, and maintenance characteristics, linear motors find widespread use in high-speed transportation systems, high-speed elevator systems and high-precision motion control systems [3, 4]. The use of stepping motors provides a simple yet effective solution to the problem of motion control compared with the use of costly DC servomotors or AC servomotors. This is especially true in applications where the external load can be closely predicted (or estimated), for example, the position control of computer peripherals, semiconductor manufacturing processes, the motion control of high-precision medical instruments and vision-based tracking systems [5]. However, stepping motors display several drawbacks including [5, 6]:

1. Losing steps. If the frequency of the input pulse train is too high and/or the external load (or the inertia load) is too large, then the stepping motor may fail to follow the pulse command faithfully.
2. Detent force. Depending on the machine structure, the detent force will cause undesired vibration and noise at certain operational speeds which will degrade the positioning accuracy and thus limit its operational range.

We now intend to design a high-performance direct-drive position-control system to overcome these difficulties using an ironless LPMSM (ILPMSM) which will allow us to eliminate the costly position and current sensors. The overall system can be thought of in terms of a PM-type linear stepping motor, however, there will be no complex toothed iron core in the stator or the mover. The position and thrust force of the mover will be controlled by regulating the orientation and magnitude of the excited space current vector of the moving coil. In addition, the positioning system to be developed will exhibit the capability of an automatic initialisation. In other words if the total position error due to losing steps is smaller than two pole pitches, the position error will be eliminated.
automatically as the abnormal conditions are removed during the travelling process.

In the direct-drive position-control system to be developed in this study, the output position will be directly related to the current waveform through the moving coils, and therefore the positioning accuracy will be highly sensitive to the dead time. This means that any disturbed voltage caused by the dead time will create unwanted position error oscillations during the travelling process. This unwanted position error will not only degrade the positioning accuracy but may also introduce serious vibration and instability problems. To cope with this problem, a cost-effective position error compensation method will be proposed to improve the positioning accuracy. In the proposed approach, the disturbed voltage caused by the dead time will be treated as an external disturbed voltage vector, which can be eliminated effectively by adding a corresponding compensation quantity to the reference voltage command. In addition, a high-performance digital signal processor (DSP), TI TMS320C2812, with a module-based drive structure will be employed to implement the proposed control algorithm. The validity of proposed approach will be experimentally tested.

2 Characteristics of an ILPMSM

Among the various types of LPMSMs, the ILPMSM has several attractive features and these include:

1. Detent force free. Since there is no iron core between the magnetic rails no detent force will exist. The vibration and noise effects of the ILPMSM can be significantly improved compared with that of general LPMSMs.

2. Low mover inertia. Without the iron core, the inertia of the mover is significantly reduced so that a higher acceleration/deceleration can be achieved.

Figure 1 illustrates the basic structure and assembly of an ILPMSM which consists of a stationary double-sided permanent-magnet rail, and a moving coil assembly [1, 2]. The U-shaped, multi-pole double-sided permanent-magnet rail is comprised of high-performance alternating polarity rare-earth magnets which are bonded to a hard chrome-plated cold-rolled steel plate. The primary winding is encapsulated in a thermally conductive epoxy. Table 1 lists the parameters of the ILPMSM adopted in this study [2].

The fundamental operation principle of the ILPMSM is that if a set of balanced three-phase currents at a given frequency (each phase current has the same magnitude but differing in phase by 120°) flow through the primary coil (consists of three separated windings spaced one-third of two pole pitches apart), then a magnet motive force (MMF) travelling wave with a constant magnitude and velocity will be produced according to the magnitude and the frequency of the excited current [3]. The linear velocity of the MMF travelling wave produced by the primary winding at steady-state conditions is the so-called synchronous velocity \( v_s \) which can be described mathematically by \( v_s = 2f_c \pi \), where \( \pi \) is the pole pitch, and \( f_c = \omega_c/2\pi = 1/T_e \) is the electric frequency of the input current.

Compared with rotary synchronous motors, the synchronous velocity of an ILPMSM depends on the input frequency of the excited current and the pole pitch of the permanent magnet, however, it does not depend on the number of magnetic poles. Considering the special case where \( f_c = 0 \), i.e. the current through each phase is fixed at an arbitrarily balanced value, then the position \( x \) of the resulting MMF axis (magnetic field) can be determined by:

\[
    x = \frac{\omega_c x}{\pi} = \frac{\theta x}{\pi} \tag{1}
\]
It is known that if the position of the axis of the MMF travelling wave is not in line with the magnetic field built by the stator, then an induced force which is referred to as the alignment force [5] will be produced. This is the force between the primary moving coil and the permanent-magnet rail that will make the primary coil tend to align with the axis of the field built by the double-sided permanent-magnet rails. Therefore, if the external load can be closely predicted or estimated, instead of using a multi-loop cascaded-feedback control structure that requires costly position and current sensors, the position and alignment force of the moving coil can be controlled by simply regulating the orientation and amplitude of the space current vector of the primary coil. Actually, the fundamental mechanism to position an ILPMSM in an open-loop fashion is similar to that of a PM-type stepping motor. Both of them are controlled by the orientation and magnitude of the magnetic alignment force, the only difference is that there is no iron core or mechanical teeth on the mover or stator in an ILPMSM as shown in Fig. 1. Therefore, the detent force and the tooling cost can be significantly reduced compared with general stepping motors. According to (1), the minimum resolution of an ILPMSM can be either determined by the pole pitch or the increment of the excitation current. However, the minimum length of the pole pitch is limited by the manufacturing process of the multiphase coil. To the best of our knowledge, the minimum length of the pole pitch is currently available commercial products is around 30–35 mm [1, 2]. In the following Sections the idea of open-loop control of an ILPMSM and its limitations will be discussed.

3 Programmable stepping resolution and holding force

Space-vector pulse-width modulation (SVPWM) is a special switching strategy for the general three-phase full-bridge inverter. It was originally proposed by Vander Broeck et al. in 1988 [7]. Compared with the switching strategy generally adopted in industry, the sinusoidal PWM (SPWM), SVPWM has two major advantages: (i) the harmonic contents of the output voltage and output current for SVPWM are less than that for SPWM and (ii) the efficiency of usage of the DC bus voltage is increased. In this study, SVPWM is used to realise the programmable stepping increment and programmable holding force for an ILPMSM. A brief introduction to the SVPWM is now presented.

Figure 2 illustrates the topology of a general six-switch full-bridge inverter. There are eight useful combinations, known as the fundamental switching states, and they are shown in Fig. 3. Table 2 lists all the possible combinations and their corresponding phase voltages. The eight fundamental voltage states can be mapped into the d-q plane using a transform matrix [8] to yield six nonzero vectors and two zero vectors as shown in Fig. 4. The six nonzero vectors can be expressed as

\[ \vec{V}_k = \frac{2}{3} \vec{V}_{dc} e^{j(k-1)\pi/3} \]

for \( k = 1, 2, \ldots, 6 \).

These eight voltage vectors, known as the basic space vectors, are denoted by \( \vec{V}_1, \vec{V}_2, \vec{V}_3, \vec{V}_4, \vec{V}_5, \vec{V}_6, \vec{V}_7 \) and \( \vec{V}_8 \). The region between two basic space vectors is called a sector, and there are six sectors defined as I–VI and shown in Fig. 4. The objective of the SVPWM switching strategy is to approximate an arbitrary voltage vector \( \vec{V}_{ref} \) by a combination of these eight switching states of the six power switches.

![Fig. 2 Topology of a general six-switch full-bridge inverter](image)

![Fig. 4 Fundamental output space voltage vectors in the d-q plane](image)
For instance, if the reference voltage vector $\mathbf{v}_{ref}$ is located in sector I, i.e. $0^\circ \leq \gamma \leq 60^\circ$ as shown in Fig. 5, with the amplitude and orientation of an arbitrary voltage vector given, the turn-on durations of $T_1$ and $T_2$ can be determined uniquely by (3) and (4) [7]:

$$T_1 = T_d m_a \frac{\sin (60 - \gamma)}{\sin 60} \quad (3)$$

$$T_2 = T_d m_a \frac{\sin \gamma}{\sin 60} \quad (4)$$

where $m_a = |\mathbf{v}_{ref}|/(2V_{dc}/3)$, and $T_d = T_1 + T_2 + T_1(T_8)$ is the PWM carrier period, $T_1$ is the $\mathbf{v}_1$ turn-on duration, $T_2$ is the $\mathbf{v}_2$ turn-on duration, and $T_1(T_8)$ is the turn-on duration of the zero-voltage vector.

![Fig. 5 An arbitrary $\mathbf{v}_{ref}$ can be expressed in terms of two adjacent voltage vectors](image)

According to (1), the position of the resulting MMF travelling wave is uniquely determined by the input phase angle of the excited current. Moreover, the value of the phase angle can be arbitrary assigned by varying the switching times $T_1$ and $T_2$ as shown in (3), and (4). Therefore, the position command of the coreless LPMSM can be converted into the orientation of the reference voltage $\mathbf{v}_{ref}$, also, the holding force and the thrust force can be modulated via $m_a$. Several advantages can be achieved using the proposed position control strategy as compared with a general stepping motor and they include:

1. The stepping angle is software programmable. The stepping angle $\delta \theta$ of the general stepping motor is determined by the number of phases ($p$) and the number of teeth of the rotor ($m$) [5], i.e.:

$$\delta \theta = \frac{360}{2pm} \quad (5)$$

According to (5), to reduce the stepping increment of the general stepping motor, one has to increase the number of phases of the motor or the number of teeth of the rotor. However, the cost of the motor drive is proportional to the number of phases, and the tooling cost is increased as the number of teeth on the rotor and the stator are increased. Moreover, because of manufacturing limitations, the number of teeth on the rotor (and the stator) cannot be increased arbitrarily. In contrast, the stepping angle based on the SVPWM-controlled strategy is determined by the switching time of each fundamental vector, which can be realised by software. The resolution of the stepping increment is solely limited by the number of bits of the micro-controller, and hence the position resolution can be increased much more easily as compared with increasing the number of mechanical teeth.

2. The holding force is software programmable. The holding force of the general hybrid stepping motor is determined by the terminal voltage of each phase, which is fixed during the positioning process. However, as the load is decreased, the copper loss and the motor temperature will also increase. Nevertheless, with the proposed control strategy, the holding force can be controlled by simply determining the amplitude modulation index $m_a$. This will make the use of stepping motors more flexible and more efficient.

3. Automatic losing step elimination capability. If an unexpected load is added to the motor or the input frequency is too high, positioning errors may occur in stepping motor applications. Such an error is often referred to as ‘losing steps’ and it will remain until the process is resumed. It is one of the major drawbacks associated with general hybrid stepping motors. With the proposed control strategy, the losing steps phenomenon can be eased significantly. Since there is no detent force between the stator and the mover of the coreless LPMSM, and since the position is controlled by the orientation of the primary moving coil set, the positioning error may be automatically eliminated when the abnormal disturbance is removed during the positioning process. For rotary PMSMs, the positioning error can be eliminated if the total error is smaller than 360/$P$, where $P$ is the number of pole pairs of the shaft. For linear PMSMs, the maximum positioning error should be less than two pole pitches, i.e. $2\tau$.

4 Analysis and compensation of positioning error

4.1 Influence of the dead time on positioning accuracy

According to the analysis in Section 3, it is known that the position of the primary mover can be controlled by regulating the orientation of the input space current vector. In other words, the positioning accuracy is directly related to the excited primary current waveform, however, the current waveform is highly sensitive to the effect of the dead time $\delta_t$ (blanking time) associated with any type of power switches. The amount of the disturbed phase voltage caused by the dead time can be expressed as [9, 10]

$$\delta V_{i=a.b.c} = \begin{cases} -\frac{\delta t}{T_d} V_{dc} & \delta t > 0 \\ +\frac{\delta t}{T_d} V_{dc} & \delta t < 0 \end{cases} \quad (6)$$

The value of the dead time is chosen so that a shoot-through or cross-conduction current through each leg of the full-bridge inverter can be avoided. Depending on the types of the power switches, the value of the dead time is around a few microseconds (1–3$\mu$s) for high-speed devices, such as MOSFETs or IGBTs. According to (6), the distortion at the zero-crossing region in the averaged voltage waveform caused by the dead time effect is illustrated in Fig. 6a. It can be seen in Fig. 6a, that the polarity of one of the three output currents changes at $0^\circ$, 60°, 120°, 180°, 240° and 300°. From Fig. 6a and (6), the effect of the dead time in each output phase voltage can be summarised as in Table 3. In addition, since the position and holding force of the moving coil are related to the orientation and magnitude of the space current vector, it is more clear to map $\delta V_{mn}$, $\delta V_{mnb}$, $\delta V_{n}$ into the $d-q$ plane to obtain the six disturbed
Effect of dead time on positioning accuracy

- Positioning error caused by dead time
- Effect of dead time on the output space current vector
- Effect of dead time on the output phase currents
- Effect of dead band on the output current waveform and the positioning accuracy for the case of uniform increment command

Equation (7) reveals that the amplitude and orientation of the disturbed voltage vector caused by the dead time is fixed in the $d$-$q$ plane during each 60°. Figure 7a illustrates the corresponding orientation in the $d$-$q$ plane with respect to the $a$-$b$-$c$ plane. Figure 6b shows the trajectories of the space voltage vector in the $d$-$q$ plane with/without the dead time effect, in which the traveling length is $2\pi$, i.e. the phase angle is from 0° to 360°. The trajectory for the ideal voltage vectors caused by the dead time, namely $\overline{\delta v_1}$, $\overline{\delta v_2}$, $\overline{\delta v_3}$, $\overline{\delta v_4}$, $\overline{\delta v_5}$, $\overline{\delta v_6}$ in, where:

$$\overline{\delta v_k} = \frac{4}{3} \frac{\delta t}{T_d} V_{dc} \sin(k-1)\frac{\pi}{3} \quad k = 1, 2, \ldots, 6 
$$

Figure 6

**Fig. 6** Effect of dead band on the output current waveform and the positioning accuracy for the case of uniform increment command

- a Effect of dead time on the output phase currents
- b Effect of dead time on the output spatial current vector
- c Effect of dead time on positioning accuracy
- d Positioning error caused by dead time

**Table 3: Amount of distortion in the phase voltage caused by the dead time**

<table>
<thead>
<tr>
<th>Phase angle $\theta_a$</th>
<th>$\delta V_{a0}$</th>
<th>$\delta V_{b0}$</th>
<th>$\delta V_{c0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°–60°</td>
<td>$-\frac{\delta t}{T_d} V_{dc}$</td>
<td>$\frac{\delta t}{T_d} V_{dc}$</td>
<td>$-\frac{\delta t}{T_d} V_{dc}$</td>
</tr>
<tr>
<td>60°–120°</td>
<td>$-\frac{\delta t}{T_d} V_{dc}$</td>
<td>$\frac{\delta t}{T_d} V_{dc}$</td>
<td>$\frac{\delta t}{T_d} V_{dc}$</td>
</tr>
<tr>
<td>120°–180°</td>
<td>$-\frac{\delta t}{T_d} V_{dc}$</td>
<td>$\frac{\delta t}{T_d} V_{dc}$</td>
<td>$-\frac{\delta t}{T_d} V_{dc}$</td>
</tr>
<tr>
<td>180°–240°</td>
<td>$\frac{\delta t}{T_d} V_{dc}$</td>
<td>$-\frac{\delta t}{T_d} V_{dc}$</td>
<td>$\frac{\delta t}{T_d} V_{dc}$</td>
</tr>
<tr>
<td>240°–300°</td>
<td>$\frac{\delta t}{T_d} V_{dc}$</td>
<td>$-\frac{\delta t}{T_d} V_{dc}$</td>
<td>$-\frac{\delta t}{T_d} V_{dc}$</td>
</tr>
<tr>
<td>300°–360°</td>
<td>$\frac{\delta t}{T_d} V_{dc}$</td>
<td>$-\frac{\delta t}{T_d} V_{dc}$</td>
<td>$-\frac{\delta t}{T_d} V_{dc}$</td>
</tr>
</tbody>
</table>

Figure 7

**Fig. 7** Disturbed and corresponding compensated voltage vector

- a Disturbed voltage vectors caused by the dead time
- b Corresponding compensated voltage vectors for the reference voltages
three-phase balanced voltage is an ideal circle, and the stepping increment of the orientation is uniform. According to (6) and Fig. 6a, it can be expected that the amplitude of the disturbed voltage vector will be decreased (the inner circle in Fig. 6b), i.e. the holding force and the thrust force will be reduced by the dead time effect. So, because of the existence of the dead zone at the zero-crossing area in the output voltage, the stepping increment is not uniform. In other words, the dead time will not only reduce the holding force but also degrade the positioning accuracy. Using (1) and Fig. 6b, it is possible to determine the position of the moving coil, and is it depicted in Fig. 6c. It is expected that unwanted position oscillation will occur during the traveling process due to the fact that the increment in the phase angle is not uniform as is shown in Fig. 6b. The position error oscillation is illustrated in Fig. 6d, such an oscillation will not only deteriorate the positioning accuracy but also result in unwanted mechanical vibrations. Figure 8 illustrates the results of circle tracking.

4.2 Positioning error compensation

The previous analysis indicates that the existence of a dead time will result in a nonlinear output voltage gain of the inverter, leading to a serious distortion in the waveforms which may cause instabilities as well as significant positioning errors when a machine is being driven. In order to improve the positioning accuracy, a cost-effective compensation strategy for the dead time effects in the d-q plane is now developed. As shown in (7) and Fig. 7a, if the zero-crossing instants of the three phase currents can be detected accurately, the amplitude and the orientation of the reference voltage command can be modified using (8) to compensate for the dead time effect:

\[ v_{\text{ref}} = v_{\text{ref}} + (-\delta v_k) \quad k = 1, 2, \ldots, 6 \]  

where \( k \) is determined by the orientation of the reference voltage.

Figure 7b depicts the corresponding compensated voltage vector which should be added to the reference voltage according to the orientation of the reference voltage. In practical implementations, the zero-crossing instants of the three phase currents can be detected accurately using various types of sensing strategies [10–12], however, most of these strategies will increase the cost and complexity of the system. An alternative approach is to directly compensate for the disturbed voltage vector as calculated in (7) using the orientation command of the reference voltage vector. The output performance is satisfactory if the output current is in-phase with the reference voltage, which is the case for low-speed applications. If the input frequency of the pulse train increases or the inductance of the motor is large, the timing of adding the compensated voltage should be advanced to avoid lagging occurring. This can be achieved due to the fact that the motion profile can be obtained from the command generator in advance.

5 Drive hardware configuration

The structure of the ILPMSM drive is similar to that of general rotary AC motors [13, 14]. The concept of a module-based drive structure is prepared and implemented in this study by considering issues such as future maintenance requirements and the flexibility for different rated power applications. The module-based drive consists of three major parts.

1. Intelligent power module (IPM). IGBT modules have been adopted extensively in AC drive applications due to their attractive characteristics such as a high-power capability and fast operating speed. Figure 9 shows the inner-circuit connection of the IGBT module (Mitsubishi CM30MD-12H) employed in this study. Modern IPMs integrate the gate-drive circuit, and protection circuits for abnormal operations, such as over-current, over-temperature, and under-voltage lock-out, etc. Compared with configurations that consist of discrete components, IPMs have several advantages such as equipment miniaturization and reduction in the time taken between conception and marketing. For differently rated power applications, the users just need to change the IPM module with the other parts remaining unchanged. The IPM module is the only part which may need to be changed to suit differently rated ILPMSM sizes.
2. Optically-coupled gate drive circuit. A 2A output current, optically-coupled IGBT gate drive HCPL-3120 is employed in this study due to its noise rejection ability and the protection of the position command generators. The HCPL-3120 consists of a GaAsP LED optically coupled to an integrated circuit with a power output stage. The voltage and the current supplied by this optocoupler can directly drive IGBTs with ranges up to 1200 V/100 A. Figure 10 illustrates the application circuit adopted in this study.

3. Fully digital position command generator. A 32-bit, highly integrated DSP, TMS320F2812, which integrates the high-performance DSP core with powerful on-chip peripherals supplied from Texas Instruments, capable of 150 MIPS, is used as the system control kernel [15]. The TMS320F2812 has a built-in hardware that greatly simplifies the generation of symmetric SVPWM waveforms. Only the software configuration is needed to generate the switching control signals of the SVPWM. Figure 11 illustrates the overall experimental configuration of the cost-effective sensorless position-control system used in a visual tracking application, where the external load can be closely predicted during the travelling process.

6 Experimental evaluation

Figures 12a and 12b show the trajectories of the space current vector as the stepping increment command $\delta x$ is decreased from $\tau/3$ to $\tau/6$, i.e. $\delta b_{\tau}$ is decreased from 60° to 30°. Instead of changing the number of teeth or the winding phases on the stator and mover, the minimum resolution of the stepping increment using the proposed control strategy can be varied by simply adjusting the related control registers of the DSP controller, i.e. it is software programmable. The radius of the trace of the space current vector shown in Fig. 12 represents the magnitude of the excited current, i.e. holding and alignment forces. In order to keep...
Fig. 12 Comparisons of measured current waveforms for various stepping increments with and without dead time compensation

a Measured excited space current vector without dead time compensation, $\delta x = \tau/3$, ($\delta \theta_2 = 60^\circ$), scale = 1 A/div
b Measured excited space current vector without dead time compensation, $\delta x = \tau/6$, ($\delta \theta_2 = 30^\circ$), scale = 1 A/div
c Measured excited space current vector without dead time compensation, $\delta x = \tau/180$, ($\delta \theta_2 = 1^\circ$), scale = 1 A/div
d Measured excited d-q axis current without dead time compensation, $\delta x = \tau/180$, ($\delta \theta_2 = 1^\circ$), scale = 2 A/div
e Measured excited space current vector with dead time compensation, $\delta x = \tau/180$, ($\delta \theta_2 = 1^\circ$), scale = 1 A/div
f Measured excited d-q axis current with dead time compensation, $\delta x = \tau/180$, ($\delta \theta_2 = 1^\circ$), scale = 2 A/div
the alignment force at a constant value during the travelling process, the magnitude of the excited voltage should be increased to keep the flux through the air-gap unchanged as the velocity of the moving coil is increased. For the cases where the moving coil is fixed so as to be against the static thrust force, the holding force should be adjusted according to the magnitude of the external force to yield the least copper loss. Figures 12c and 12d illustrate the trajectories of the direct and quadrature currents, \( i_d \), \( i_q \), in the d-q plane and the time domain where the stepping increment \( \Delta x = \tau/180 \) is chosen to be relatively small (\( \Delta \theta_k = \tau/180 \)). Because of the dead time effect, it can be seen that the trajectory is not an ideal circle, moreover, the stepping increment is not uniform, for which these phenomena have been analysed in Section 4. Figure 12d shows the distorted direct and quadrature current waveforms in the time domain, where the waveforms are significantly distorted and are far from ideal sinusoids. According to the preceding analysis, the distortion in the excited current will not only reduce the alignment and holding forces but also deteriorate the positioning accuracy. Figures 12e and 12f illustrate the trajectories of the space current vector in the d-q plane and in the time domain respectively, where the dead time effect is compensated with the proposed strategy discussed in Section 4.2. It is easy to see that the waveforms of the excited space current have been refined, i.e. the positioning accuracy can be improved significantly.

According to (1), position information can be predicted from the phase angle of the excited current. In order to verify the positional accuracy of a linear stage using the proposed control strategy, a linear optical encoder was used to measure the output position (Fig. 11). It has two output channels, phase A and phase B, which are 90° apart. Because of quadrature between different channels, there are two rising and falling edges over one cycle. Therefore, the resolution of a 5 μm linear encoder for each phase can be refined to 1.25 μm. Figure 13 shows the step position response over two pole pitches, i.e. one electric cycle. It can be seen that the overshoot can be reduced significantly if the stepping increment is reduced. Figure 14 shows the results of tracking control of the ramp position command without and with position error compensation. As analyzed in Section 4, the position error obtained with the proposed control strategy is mainly due to the switching dead time. As shown in Fig. 14a, the switching dead time will not only deteriorate the positioning accuracy but also introduce significant high-frequency vibrations which may cause mechanical instability. In contrast, with the proposed compensation strategy, the position error is reduced significantly as illustrated in Fig. 14b. Figure 15 shows the

![Fig. 13 Step response with different step increments](image)

**Fig. 13** Step response with different step increments

* a Position response, \( \Delta x = \tau/3 \)
* b Position response, \( \Delta x = \tau/30 \)

![Fig. 14 Tracking control of ramp position command without and with position error compensation](image)

**Fig. 14** Tracking control of ramp position command without and with position error compensation

* a Position response without dead time compensation
* b Position response with proposed dead time compensation
position response for the case where the linear stage is under external disturbance. As mentioned in Section 3, if the losing steps caused by the unexpected force are within two pole pitches, the linear stage will go back to its original position when the external disturbance stops. Namely, the proposed control strategy has an automatic losing step elimination capability.

7 Conclusions

The position of a direct-drive ILPMSM has been precisely controlled by regulating the space current vector of the primary moving coil without using costly position or current sensors. With the proposed control strategy, the direct-drive position-control system can be thought of as a PM-type linear stepping motor, however, there are no teeth on the mover or the stator. It is particularly suitable for motion control applications in which the external load is constant or can be well predicted. It has been shown that the disturbed voltage caused by the dead time will result in unwanted position errors and oscillations. This will not only degrade the positioning accuracy but may also introduce serious vibration and instability problems. A simple and effective position error compensation method was proposed to improve the positioning accuracy. The disturbed voltage is treated as an external disturbed voltage vector, which is effectively eliminated by adding the corresponding quantity to the reference voltage command. A high-performance DSP accompanied with a modular-based drive was used to implement the proposed control strategy. The advantages of the proposed control strategy over a general hybrid stepping motor include that the stepping increment, holding force, and thrust force of the ILPMSM are software programmable. Also, the position error caused by losing steps can be eliminated if the abnormal conditions are removed during the tracking process. In addition there is no detent force during the tracking process and a higher acceleration can be achieved.

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