Analysis and Reduction of Detent Effect in Magnetic Lead Screws With Parallel Magnetized Permanent Magnet Segments

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ABSTRACT

This paper deals with the analysis and suppression of detent effect in the magnetic lead screw (MLS), which is equipped with parallel magnetized permanent magnet (PM) segments to approximate the helical PM for manufacturing simplicity. The detent effect is caused by the non-uniform magnetization along the helical PM, and behaves as both thrust force ripple and torque ripple during the transmission process. In this paper, a three-dimensional (3-D) analytical model of the MLS is established to analyze and predict the air-gap magnetic field, and the thrust force and torque are then derived, as well as their ripple components. It demonstrates that the harmonic order of the ripples is solely dependent on PM segments’ quantities per helix turn on both the nut and screw. The analytical analysis is verified by extensive 3-D numerical computations. The impact of load angle and quantities of PM segments on the detent effect are investigated. It’s shown that the torque ripple suffers more seriously than thrust force ripple, and both ripple percentages drop with the increase of load angle. And it is highlighted that larger least common multiple of PM segments’ quantities on screw and nut is conducive to improving the average values of thrust force and torque, and reducing the detent effect.

INDEX TERMS

Analytical model, detent effect, magnetic lead screw, thrust force ripple, torque ripple.

I. INTRODUCTION

Due to the advantages of physical isolation between moving parts, no gear lubrication, overload protection and reduced maintenance [1], magnetic transmission has drawn increased attention in recent years. Most magnetic transmission mechanisms can be regarded as the counterpart of traditional mechanical systems [2]. The magnetic lead screw (MLS) is a device analog to the mechanical ball screw, and its function is converting rotation into linear motion or vice versa. Benefiting from high reliability, high motion precision and improved force/torque density, the MLS has been considered as a promising candidate in many applications, such as wave energy conversion [3], [4], artificial hearts [5], vehicle active suspension systems [6].

An MLS contains two components: a magnetic nut and a magnetic screw, and they are shown in Fig. 1. To realize the energy conversion between linear motion and rotation, radially magnetized helical-shape permanent magnets (PMs) with different polarities are mounted on both the interior surface of nut and exterior surface of screw, alternately. However, it costs much to manufacture the ideal radially magnetized PM with helical shape. Therefore, lots of designs were developed to simplify the structure of MLS. Arc-segmented PMs were proposed to substitute the helical PMs in [7] and [8], and the effect of arc PM segments on the MLS performance were also investigated. Different kinds of skewed arc-segmented PMs were used to approximate the ideal helical ones in [9] and [10]. In [11] and [12], Halbach and flux concentration PM pole designs were also proposed to facilitate the manufacture of MLS and improve the force density. However, it should be noted that most of the simplification techniques above mainly focused on the approximation of the helical-shape PMs. The magnetization pattern of PM segment was rarely considered. In literature, radial magnetization was usually adopted by default. Actually, parallel magnetization is
more commercially-available for the PM segments, and as will be highlighted in the paper, it will result in considerable alterations of the MLS performance, especially the thrust force ripple and torque ripple caused by the detent effect. Quite recently, the authors of this paper have established a three-dimensional (3-D) analytical model of the MLS equipped with parallel magnetized PM segments, and the air-gap magnetic field, thrust force and torque were predicted precisely [13]. Nevertheless, much attention was paid solely to the static characteristics. As a kind of double-mechanical-port electromagnetic device, the transmission characteristics, which mainly refer to the thrust force/torque characteristics when the nut and screw travel simultaneously, either in synchronism or in asynchronism, is also very important for the MLS. However, the transmission characteristics, especially the detent effect of MLS, were not well investigated.

The transmission characteristics is quite essential for the magnetic transmission systems. From the view of motion systems, it is generally expected to suffer less torque or force ripple to guarantee stability and precision of transmission processes. Due to the cogging torque in magnetic gears, the transmission torque of magnetic gears is concerned [14]–[18]. The transmission torque of magnetic gear was mathematically formulated and the harmonic order of the cogging torque is described in [19]. The effect of flux-modulator shape on the transmission torque of magnetic gear was investigated to reduce the torque ripple in [20] and [21]. For the MLS, although cogging effect doesn’t exist in principle, non-ideal radially magnetized PMs will also result in thrust force ripple and torque ripple. However, the transmission characteristics of the MLS were rarely investigated in previous literatures.

In this paper, the detent effect of the parallel magnetized MLS is revealed and analyzed with a 3-D analytical method. In Section II, the principle of the detent effect in the MLS is described. A 3-D analytical model of the MLS with parallel magnetized PM segments is proposed in Section III, and validated by 3-D FEM in Section IV. Discussions on the suppression of the detent effect are presented in Section V, and thereafter, the conclusions are drawn.

The innovation of the paper lies that: 1) A 3-D analytical model of MLS is presented to predict the detent effect in an accurate way. 2) The cause of the detent effect is revealed in physical sense, which lies in the non-ideal air-gap magnetic field induced by the non-uniform magnetization along the helical PM. 3) Effective counter-measures are proposed to reduce the detent effect of the MLS.

II. OPERATING PRINCIPLE AND DETENT EFFECT

A. OPERATING PRINCIPLE

Due to the helical shape of PMs, simultaneous thrust force and torque are applied on both the nut and screw during the transmission. The thrust force $F$ and torque $T$ have a constant ratio, i.e. the transmission ratio $G$, expressed as

$$G = \frac{F}{T} = \frac{\omega}{\nu} = \pm \frac{\pi}{\tau_p} \quad (1)$$

where $\omega$ and $\nu$ are the angular and linear velocity, respectively, and $\tau_p$ is the pole pitch of MLS.

The positive directions of thrust force and torque refer to the axial direction and angular direction, respectively, in Fig. 1. The sign of transmission ratio is dependent on the direction of PM helix, either left-handed or right-handed. Left-handed PM helix results in a negative transmission ratio, and right-handed PM helix results in a positive transmission ratio. The MLS investigated in this paper is right-handed.

Similar to magnetic gears or couplings, the values of thrust force and torque of MLS are determined by the relative position between the nut and screw. However, the position of helical PM could be measured from both axial and angular directions, as indicated in Fig. 2. The load angle $\delta$ is defined as

$$\delta = \Delta \theta + G \cdot \Delta z \quad (2)$$

where $\Delta \theta$ and $\Delta z$ denote the angular and axial position difference, respectively. And the thrust force and torque on screw can be approximated as

$$T \approx T_m \sin \delta \quad (3)$$

$$F = G \cdot T \approx G \cdot T_m \sin \delta \quad (4)$$

where $T_m$ is the pull-out torque.

B. DETENT EFFECT

One of the challenges to popularize the MLS lies in the realization of radially magnetized helical PMs. To achieve high force density, sintered NdFeB PMs are usually adopted in the MLS. However, it’s hard to manufacture continuous sintered NdFeB PMs with standard radial magnetization. Anyhow, discretized helical NdFeB PM segments could be regarded as an alternative solution. Fig. 3 depicts the interior and exterior turns of PM helices composed by 12 helical segments. Compared to the radial magnetization, parallel magnetization for
NdFeB PM segments is more cost-effective. Therefore, the MLS investigated in this paper is confined to those equipped with the parallel magnetized PM segments.

Operating on the principle of minimum magnetic reluctance, PM segments on screw and nut tend to be aligned with each other in angular direction, as shown in Fig. 4 (a), even in the case that the load angle $\delta$ is zero. When the segments are unaligned in angular direction, extra force and torque will be generated to reset the PM segment, as shown in Fig. 4 (b). During the transmission between linear motion and rotation, relative angular position between screw and nut would be changing all the time, and it would result in ripples of both the thrust force and torque. This is called the detent effect in the MLS. It should be emphasized that for the ideal MLS, since the air-gap magnetic field is uniform along the helix, there’s no detent effect in it. The detent effect only exists in the MLS equipped with parallel magnetized PM segments.

The concept of ‘detent effect’ (or called ‘cogging effect’) is far from new in PM machines, and it is originating from the interaction between the stator tooth-slots and the rotor magnet flux in the absence of stator currents. Nevertheless, the detent effect in the MLS is essentially different from that in PM machines, since there are no teeth or slots on either the screw or nut.

III. 3-D ANALYTICAL MODEL FOR DETENT EFFECT ANALYSIS

Due to the helical PM segments, the distribution of magnetic field in MLS is essentially 3-D. Apart from numerical approach for field computation, such as 3-D FEM, an accurate 3-D analytical approach is highly desirable considering the complexity of geometry model and the computation time. Although a 3-D analytical model of MLS has been proposed in [13], it’s a global solution, and it fails to take the difference of the magnetic field harmonics caused by PMs on the nut and screw into consideration. Thus, in this section, a 3-D analytical model utilizing superposition principle is proposed for analyzing the detent effect of the magnetic lead screw. It should be noted that since the solution format of partial differential equations (PDEs) and the magnetization vector of PMs in both models are essentially identical, the details will be simplified in this paper.

A. BOUNDARY VALUE PROBLEMS OF 3-D ANALYTICAL MODEL

The air-gap magnetic field is excited together by PMs on the screw and nut. When the numbers of PM segments on the screw and nut are different, the orders of magnetic field harmonics excited by screw and nut are also different from each other. Hence, the fields excited by the screw and nut will be calculated separately in this paper, and then they are added together to obtain the distribution of the resultant air-gap magnetic field.

Fig. 5 shows the analytical models for calculating the magnetic fields by the screw and nut. In the case of screw model, PMs on the nut are removed. The screw model is divided into two regions, viz. PM region (Region I) and air gap region (Region IIa), as shown in Fig. 5 (a). On the contrary, PMs on the screw are removed in the case of nut model, and the air gap region (Region Iib) and PM region (Region III) are created, as shown in Fig. 5 (b). $N_s$ and $N_e$ denote the quantity of PM segment within one turn of PM helix on screw and nut, respectively. $R_1$, $R_2$, $R_3$ and $R_4$ indicate the boundary radii of the four regions.

In order to formulate the analytical model, back irons of screw and nut are assumed to be with infinite permeabilities. And the end effect due to finite length of back irons is also
neglected. The magnetic scalar potential \( \phi \) is selected to formulate the magnetic field distribution of MLS. The governing equations are

\[
\begin{align*}
\nabla^2 \phi_i &= \frac{1}{\mu_r} \nabla \cdot \mathbf{M}_i & (i = I, III) \\
\nabla^2 \phi_{ii} &= 0 & (i = a, b)
\end{align*}
\]

(5)

where \( \mu_r \) denotes the relative recoil permeability of PMs. The magnetic field intensity \( \mathbf{H} \) and flux density \( \mathbf{B} \) in every region could be obtained by

\[
\begin{align*}
\mathbf{H}_i &= -\nabla \phi_i \\
\mathbf{B}_{ii} &= \mu_0 \mathbf{H}_{ii} & (i = a, b)
\end{align*}
\]

(6)

(7)

In the case of screw model, the boundary conditions are

\[
\begin{align*}
\mathbf{H}_i(z) &= 0 \quad \text{if} \quad r = R_1, \\
\mathbf{H}_i(\theta) &= 0 \quad \text{if} \quad r = R_1, \\
\mathbf{H}_{Ia} &= 0 \quad \text{if} \quad r = R_k, \\
\mathbf{H}_{Ia} &= 0 \quad \text{if} \quad r = R_k, \\
\mathbf{H}_{Ib} &= \mathbf{H}_{Ib} |_{r = R_2}, \\
\mathbf{B}_{Ib} &= \mathbf{B}_{Ib} |_{r = R_2}.
\end{align*}
\]

(8)

In the case of nut model, the boundary conditions are

\[
\begin{align*}
\mathbf{H}_{IIa} &= 0 \quad \text{if} \quad r = R_1, \\
\mathbf{H}_{IIb} &= 0 \quad \text{if} \quad r = R_1, \\
\mathbf{H}_{IIa} &= 0 \quad \text{if} \quad r = R_k, \\
\mathbf{H}_{IIb} &= 0 \quad \text{if} \quad r = R_k, \\
\mathbf{H}_{IIc} &= \mathbf{H}_{IIc} |_{r = R_3}, \\
\mathbf{B}_{IIr} &= \mathbf{B}_{IIr} |_{r = R_3}.
\end{align*}
\]

(9)

where \( H_{Ir} \), \( H_{Ib} \) and \( H_{Ic} \) represent the radial, angular and axial components of magnetic field intensity \( \mathbf{H} \), respectively, in region \( i \) \( (i = I, IIa, IIb, \text{and } III) \). And \( \mathbf{B} \) is the radial component of flux density \( \mathbf{B} \) in region \( i \).

**B. SOLUTION OF AIR-GAP FLUX DENSITY**

With the boundary conditions, the boundary value problem could be solved by separation of variables. The components of air-gap flux density in both models are given by (10)–(15), as shown at the bottom of this page, with

\[
\begin{align*}
\mathbf{u}_{n,k}^a &= n + k N_i, \quad \mathbf{w}_{n,k}^a &= n - k N_i, \\
\mathbf{u}_{n,k}^b &= n + k N_e, \quad \mathbf{w}_{n,k}^b &= n - k N_e.
\end{align*}
\]

(16)

where \( I_1(y) \) and \( K_1(y) \) are modified Bessel functions of the first and second kind, respectively, of \( x \)-order with argument \( y \); and \( c_{n,k}^{IIa} \), \( c_{n,k}^{IIb} \), \( c_{n,k}^{IIc} \), \( d_{n,k}^{IIa} \), \( d_{n,k}^{IIb} \) and \( d_{n,k}^{IIc} \) are coefficients defined in Appendix.

Thus, the resultant air-gap flux density could be obtained by

\[
\begin{align*}
\mathbf{B}_{IIr}(r, \theta, z) &= \mathbf{B}_{IIa}(r, \theta, z) + \mathbf{B}_{IIb}(r, \theta, z) \quad R_2 < r < R_3 \\
\mathbf{B}_{IIr}(r, \theta, z) &= \mathbf{B}_{IIa}(r, \theta, z) + \mathbf{B}_{IIb}(r, \theta, z) \quad R_2 < r < R_3 \\
\mathbf{B}_{IIr}(r, \theta, z) &= \mathbf{B}_{IIa}(r, \theta, z) + \mathbf{B}_{IIb}(r, \theta, z) \quad R_2 < r < R_3
\end{align*}
\]

(17)
C. EXPRESSIONS OF THRUST FORCE AND TORQUE

The thrust force and torque of MLS are calculated with Maxwell stress tensor method, and are given by

\[
F = \frac{R_d}{\mu_0} \int_0^l \int_0^{2\pi} B_{IIr} (R_d, \theta, z) B_{IIz} (R_d, \theta, z) d\theta dz \quad (18)
\]

\[
T = \frac{R_d^2}{\mu_0} \int_0^l \int_0^{2\pi} B_{IIr} (R_d, \theta, z) B_{II\theta} (R_d, \theta, z) d\theta dz \quad (19)
\]

where \( l \) is the axial length of the magnetically coupled area in MLS, and \( R_a \) is the average radius of air gap \( (R_a = (R_2 + R_1)/2) \).

To investigate the detent effect of the MLS, the screw is set to be motionless, and the nut has a two-degree of freedom, axial and angular directions. According to (10)\textemdash(15), the airgap flux density components is the sum of infinite harmonic terms, and the harmonic term due to the screw can be generally written as

\[
b_{ar} = A \sin [(n_1 \pm k_1 N_1) \theta - n_1 \pi z/\tau] \quad (20)
\]

\[
b_{a\theta} = B \cos [(n_1 \pm k_1 N_1) \theta - n_1 \pi z/\tau] \quad (21)
\]

\[
b_{az} = C \cos [(n_1 \pm k_1 N_1) \theta - n_1 \pi z/\tau] \quad (22)
\]

The harmonic term due to the nut can be generally written as

\[
b_{br} = D \sin [(n_2 \pm k_2 N_e) \theta - \Delta \theta - n_2 \pi (z - \Delta z)/\tau] \quad (23)
\]

\[
b_{b\theta} = E \cos [(n_2 \pm k_2 N_e) \theta - \Delta \theta - n_2 \pi (z - \Delta z)/\tau] \quad (24)
\]

\[
b_{b\zeta} = F \cos [(n_2 \pm k_2 N_e) \theta - \Delta \theta - n_2 \pi (z - \Delta z)/\tau] \quad (25)
\]

where \( n_1 \) and \( n_2 \) are positive odd numbers, \( k_1 \) and \( k_2 \) are non-negative integers, and \( A, B, C, D, E \) and \( F \) are constants independent of \( \theta \) and \( z \). Thus, it yields (26), as shown at the bottom of this page.

It can be found that the torque can be regarded as a function about axial and angular positions of nut, and not all the magnetic field harmonics contribute to the torque of MLS. It’s worth noting that the harmonic order about angular positions is different from that about axial position. The angular harmonic order is given by

\[
|n_2 \pm kU| = |n_2 \pm k_1 N_1| = |n_2 \pm k_2 N_e| \quad (27)
\]

### TABLE 1. Primary parameters of an MLS.

| Symbol | Parameter | Value |
|--------|-----------|-------|
| \( R_1 \) | Inner radius of the PM on screw (mm) | 20 |
| \( R_2 \) | Outer radius of the PM on screw (mm) | 25 |
| \( R_3 \) | Inner radius of the PM on nut (mm) | 26 |
| \( R_4 \) | Outer radius of the PM on nut (mm) | 31 |
| \( \tau_p \) | Pole pitch (mm) | 8 |
| \( \sigma \) | Pole width coefficient | 1 |
| \( l \) | Axial length of magnetically coupled area (mm) | 48 |
| \( N_i \) | Quantity of screw PM segments per helix turn | 6 |
| \( N_e \) | Quantity of nut PM segments per helix turn | 6 |
| \( B_{rem} \) | Remanent flux density of PM (T) | 1.25 |
| \( \mu_r \) | Relative recoil permeability of PM | 1.06 |

where \( U \) is the least common multiple (LCM) of \( N_i \) and \( N_e \), and \( k \) is a nonnegative integer, and the axial harmonic order is \( n_2 \), which will result in different torque characteristics.

Furthermore, (26) can be rewritten as

\[
\int_0^l \int_0^{2\pi} (b_{ar} + b_{br}) (b_{a\theta} + b_{b\theta}) d\theta dz = (AD - BC) \pi l \sin (n_2 \delta \pm kU \Delta \theta), \quad n_1 = n_2 & k_1 N_1 = k_2 N_e \quad (28)
\]

The value of torque is dependent on the load angle and the angular position of nut. Specifically, the average torque and the ripple torque are separated, as follows:

1) Average torque: the average torque corresponds to the case that \( n_1 = n_2 \) and \( k = 0 \), and its value is only dependent on the load angle.

2) Ripple torque: in the case of \( n_1 = n_2 \) and \( k \neq 0 \), the rotation of the nut would result in a torque component fluctuating with the angular position, i.e. ripple torque. And the order of torque ripple is \( kU \).

Likewise, the analysis above can be also applied to the analysis of the average thrust force and force ripple.

### IV. NUMERICAL VALIDATIONS

In this section, 3-D FEM is implemented to validate the proposed 3-D analytical model. The primary parameters of
an MLS equipped with parallel magnetized PM segments is listed in Table 1.

A. CHARACTERISTICS OF THRUST FORCE AND TORQUE

According to (26), the thrust force and torque of the MLS are determined by both axial and angular positions of the nut. If the axial position of the nut is constant, the load angle will be linear with the nut’s angular position, and the waveforms of thrust force and torque are be obtained by using the proposed 3-D analytical model, as shown in Fig. 6 (a) and (b). In the meanwhile, as a comparison, corresponding waveforms by 3-D FEM are also shown in Fig. 6. Fast Fourier transform is performed on the thrust force and torque waveforms, and the results are shown in Fig. 6 (c) and (d). Similarly, the thrust force and torque waveforms as a function of axial position and the corresponding harmonics are shown in Fig. 7.

It’s observed that the 3-D analytical results are in good agreement with the 3-D FEM results in terms of harmonic amplitudes and orders. Fig. 6 and Fig. 7 have demonstrated that angular position and axial position result in different characteristics of thrust force and torque. Specifically, the torque waveform suffers from severe high-order harmonics due to angular position, and the harmonic order is equal to $|n_2 \pm kU|$. By contrast, the waveforms of thrust force and torque are closer to be sinusoidal as indicated by (2), with low harmonic order $n_2$.

B. THRUST FORCE RIPPLE AND TORQUE RIPPLE

There will exist thrust force ripple and torque ripple with the angular position when the nut moves along the ideal helix according to (28). The waveforms of thrust force and torque are shown in Fig. 8 (a) and (b), with a load angle of 30°. It’s evident that the thrust force and torque fluctuate with the angular position 6 times in the range of 360° axial position. The harmonics of ripples are shown in Fig. 8 (c) and (d), and the harmonic order is equal to $kU$. The 3-D analytical results are verified by 3-D FEM results, which demonstrates the effectiveness and accuracy of the proposed 3-D model.
V. FURTHER DISCUSSIONS

A. EFFECT OF LOAD ANGLE

According to (26) and (28), the thrust force and torque of the MLS is a function of two variables: one is angular position, the other one can be any one of the load torque and axial position. With the two variables, other dependent variables can be obtained from (2). Thus, the characteristics of thrust force and torque can be represented by contour plots with color filled. Fig. 9 and Fig. 10 depict the thrust force and torque maps versus load angle and angular position, respectively.

These maps are obtained by sweeping the load angle and angular position with the proposed 3-D analytical model, which is more efficient than 3-D FEM. The contour lines in Fig. 9 and Fig. 10 indicate how the load angle varies with angular position when thrust force and torque are constant. It’s observed that the load angle fluctuates 6 times when the nut rotates 360° and the greater thrust force and torque, the more obvious the fluctuation of load angle will be. The contour lines even disconnect when thrust force and torque reach 2015N and 5.19Nm, respectively. Comparatively speaking, the load angle in torque map encounters more severe fluctuation than in thrust force map, which means the torque ripple is severer than the thrust force ripple. The fluctuation of load angle indicates that the nut’s helical movement will not be perfect, and fluctuation of velocity will be caused. In summary, the detent effect behaves as load angle ripple with constant transmission thrust force and torque, or thrust force ripple and torque ripple with constant load angle.

To evaluate the level of thrust force ripple and torque ripple, the percentage that peak-to-peak value of ripple accounts for the average value is adopted. Fig. 11 shows the thrust force percentage that peak-to-peak value of ripple accounts for the average value.

FIGURE 8. Waveforms and harmonics of thrust force and torque during the transmission process. (a) Thrust force waveform. (b) Torque waveform. (c) Thrust force harmonics. (d) Torque harmonics.

FIGURE 9. Thrust force map versus load angle and angular position.

FIGURE 10. Torque map versus load angle and angular position.

FIGURE 11. Percentages of thrust force ripple and torque ripple versus load angle when \( N_i = N_e = 6 \).
ripple and torque ripple versus load angle when \( N_i = N_e = 6 \). As will be seen, with the rising of load angle, the percentage of thrust force ripple and torque ripple decline sharply at first. And then, thrust force ripple tends to stabilize at a lower level of 1.7%, however, torque ripple keeps gradually declining from 40% to 4%. It’s observed that the level of torque ripple is much higher than that of thrust force ripple. For a given load angle, the percentage of torque ripple is much higher than that of thrust force ripple. The torque ripple could reach up to 170%, while the thrust force ripple is not higher than 4%. The angular magnetization component of PM segment may be accounted for the ripple difference between thrust force and torque. Compared with that in radially-magnetized MLS, the harmonic in the angular magnetization component of PM is more serious in the parallel-magnetized MLS, and it leads to rich harmonic contents in the angular components of the air-gap flux density, i.e. \( B_{II\theta} \). From (18) and (19), it can be observed that the torque is sensitive to \( B_{II\theta} \), while the thrust force fails. Therefore, the percentage of torque ripple is vastly higher than that of force ripple.

Since the torque ripple percentage would be very high at a lower load angle, it’s recommended to set the working point at a higher load angle in the design of MLS so that the transmission will be steadier.

**B. EFFECT OF PM SEGMENTS’ QUANTITIES PER HELIX TURN**

The quantities of PM segments per helix turn on nut and screw, \( N_i \) and \( N_e \), could be random. However, the combination of \( N_i \) and \( N_e \) is related to the order of thrust force and torque ripple, as indicated by (28). Therefore, it’s essential to investigate the effect of PM segments’ quantities combinations on the detent effect.

Since \( N_i \) and \( N_e \) are random, numerous combinations of would be obtained, and it’s more operable to fix one of the two variables and change the other to simplify the comparison.

Fig. 12 depicts the comparisons of the torque and thrust force with variation of \( N_i \). As will be seen, the amplitudes of both the thrust force and torque increase with the increase of \( N_i \). In addition, the peak values of thrust force and torque almost remain stable when \( N_i \) is not smaller than 8. Therefore, considering the performance as well as the assembly difficulty, the PM segments’ quantity per helix turn on screw \( N_i \) is fixed at 8, and the corresponding quantity on nut \( N_e \) varies from 6 to 10.

Fig. 13 compares the thrust force with different combinations of \( N_i \) and \( N_e \) (\( \theta = 60\,\text{deg} \)).

![FIGURE 12. Comparison of harmonic amplitudes with different values of \( N_i \). (a) Torque. (b) Thrust force.](image)

![FIGURE 13. Comparison of thrust force with different combinations of \( N_i \) and \( N_e \) (\( \theta = 60\,\text{deg} \)).](image)

![FIGURE 14. Comparison of torque with different combinations of \( N_i \) and \( N_e \) (\( \theta = 60\,\text{deg} \)).](image)
of PM segments on screw and nut, Ni and Ne, should not

torque. To reduce the detent effect of the MLS, the quantities

thrust force ripple, and both ripples drop with the rise of load

angle. Comparatively, the torque ripple is more serious than

ripple with constant transmission thrust force and torque,

those of 3-D FEM. The detent effect behaves as load angle

The analytical results, including waveforms and harmonics

ments has been analyzed in this paper. A 3-D analytical

The detent effect of MLS with parallel magnetized PM seg-

lower load angles.

As will be seen, in comparison

to Fig. 11, both the thrust force ripple and torque ripple have

reached a pretty lower level, even when the MLS operates at

load angles in the case of $N_i = 8$ and $N_e = 10$. As will be seen, in comparison

to Fig. 11, both the thrust force ripple and torque ripple have

reached a pretty lower level, even when the MLS operates at

load angles.

VI. CONCLUSION

The detent effect of MLS with parallel magnetized PM seg-

ments has been analyzed in this paper. A 3-D analytical model has been established to predict the air-gap magnetic field distribution of the MLS, and the generation of thrust force and torque is analyzed based on the harmonic orders. The analytical results, including waveforms and harmonics of thrust force and torque, are all in good agreement with those of 3-D FEM. The detent effect behaves as load angle ripple with constant transmission thrust force and torque, or thrust force ripple and torque ripple with constant load angle. Comparatively, the torque ripple is more serious than thrust force ripple, and both ripples drop with the rise of load angle. The increase of PM segments’ quantity per helix turn is beneficial to improving the average value of thrust force and torque. To reduce the detent effect of the MLS, the quantities of PM segments on screw and nut, Ni and Ne, should not

be equal, to make the LCM of Ni and Ne as higher as possible.

APPENDIX

According to the boundary conditions, a series of linear equations about the coefficients, $a_{n,k}^{IIa}$, $b_{n,k}^{IIa}$, $a_{n,k}^{IIb}$, $b_{n,k}^{IIb}$, $c_{n,k}^{IIa}$, $d_{n,k}^{IIa}$, $c_{n,k}^{IIb}$, and $d_{n,k}^{IIb}$ will be listed. For clarity, all constants in equations will be denoted by some new symbols. Let

\[ s^1_{n,k} = I_{d_{n,k}^*(m_n R_1)}, \quad s^2_{n,k} = K_{d_{n,k}^*(m_n R_1)}, \]

\[ s^3_{n,k} = I_{d_{n,k}^*(m_n R_4)}, \quad s^4_{n,k} = K_{d_{n,k}^*(m_n R_4)}, \]

\[ s^5_{n,k} = I_{d_{n,k}^*(m_n R_2)}, \quad s^6_{n,k} = K_{d_{n,k}^*(m_n R_2)}, \]

\[ s^7_{n,k} = I_{d_{n,k}^*(m_n R_2)} + I_{u_{d_{n,k}^*(1)}(m_n R_2)}, \]

\[ s^8_{n,k} = K_{d_{n,k}^*(1)}(m_n R_2) + K_{d_{n,k}^*(1)}(m_n R_2). \]  

(A1)

\[ t^1_{n,k} = I_{d_{n,k}^*(m_n R_1)}, \quad t^2_{n,k} = K_{d_{n,k}^*(m_n R_1)}, \]

\[ t^3_{n,k} = I_{d_{n,k}^*(m_n R_4)}, \quad t^4_{n,k} = K_{d_{n,k}^*(m_n R_4)}, \]

\[ t^5_{n,k} = I_{d_{n,k}^*(m_n R_3)}, \quad t^6_{n,k} = K_{d_{n,k}^*(m_n R_3)}, \]

\[ t^7_{n,k} = I_{d_{n,k}^*(m_n R_3)} + I_{u_{d_{n,k}^*(1)}(m_n R_3)} + \frac{R_2}{R_1}, \quad C_{n,k}^{IIa} = I_{d_{n,k}^*(m_n R_3)} + K_{d_{n,k}^*(m_n R_3)}. \]  

(A2)

\[ G_{n,k}^{IIa} = I_{d_{n,k}^*(m_n R_2)} \int_{R_1}^{R_2} K_{d_{n,k}^*(m_n v)} dv - K_{d_{n,k}^*(m_n R_2)} \int_{R_1}^{R_2} I_{d_{n,k}^*(m_n v)} dv \]  

(A3)

\[ G_{n,k}^{IIb} = I_{d_{n,k}^*(m_n R_3)} \int_{R_4}^{R_5} K_{d_{n,k}^*(m_n v)} dv - K_{d_{n,k}^*(m_n R_3)} \int_{R_4}^{R_5} I_{d_{n,k}^*(m_n v)} dv \]  

(A4)

\[ G_{n,k}^{IIa} = \frac{1}{2} \left[ I_{d_{n,k}^*(m_n R_2)} + I_{u_{d_{n,k}^*(1)}(m_n R_2)} \right] \int_{R_1}^{R_2} K_{d_{n,k}^*(m_n v)} dv + \frac{1}{2} \left[ K_{d_{n,k}^*(m_n R_2)} + K_{d_{n,k}^*(1)(m_n R_2)} \right] \int_{R_1}^{R_2} I_{d_{n,k}^*(m_n v)} dv \]  

(A5)

\[ G_{n,k}^{IIb} = \frac{1}{2} \left[ I_{d_{n,k}^*(m_n R_3)} + I_{u_{d_{n,k}^*(1)}(m_n R_3)} \right] \int_{R_4}^{R_5} K_{d_{n,k}^*(m_n v)} dv + \frac{1}{2} \left[ K_{d_{n,k}^*(m_n R_3)} + K_{d_{n,k}^*(1)(m_n R_3)} \right] \int_{R_4}^{R_5} I_{d_{n,k}^*(m_n v)} dv \]  

(A6)
The symbols $G_{n,k}^{i}$ and $G_{n,k}^{m}$ are the reflection of PMs as the magnetic source in region $i$ ($i = I, III$). With these new symbols, the linear equations can be rewritten as matrix format. Let

$$\begin{align*}
S_{n,k} &= \begin{pmatrix}
\frac{s_{1,n,k}}{2} & \frac{s_{2,n,k}}{2} & 0 & 0 \\
-\frac{s_{2,n,k}}{2} & \frac{s_{1,n,k}}{2} & 0 & 0 \\
0 & 0 & \frac{s_{3,n,k}}{2} & \frac{s_{4,n,k}}{2} \\
0 & 0 & -\frac{s_{4,n,k}}{2} & -\frac{s_{3,n,k}}{2}
\end{pmatrix} \\
T_{n,k} &= \begin{pmatrix}
\frac{t_{1,n,k}}{2} & \frac{t_{2,n,k}}{2} & 0 & 0 \\
-\frac{t_{2,n,k}}{2} & -\frac{t_{1,n,k}}{2} & 0 & 0 \\
0 & 0 & \frac{t_{3,n,k}}{2} & \frac{t_{4,n,k}}{2} \\
0 & 0 & -\frac{t_{4,n,k}}{2} & -\frac{t_{3,n,k}}{2}
\end{pmatrix} \\
X_{n,k} &= (a_{n,k}^{I} b_{n,k}^{I})' \\
Y_{n,k} &= (a_{n,k}^{II} b_{n,k}^{II})'
\end{align*}$$

(A7)

The coefficients, $a_{n,k}^{I}$, $b_{n,k}^{I}$, $a_{n,k}^{II}$, and $b_{n,k}^{II}$, can be obtained by solving the following linear equations:

$$\begin{align*}
S_{n,k} X_{n,k} &= A_{n,k} \\
T_{n,k} Y_{n,k} &= B_{n,k}
\end{align*}$$

(A8)

Also, the coefficients, $a_{n,k}^{I}$, $b_{n,k}^{I}$, $a_{n,k}^{II}$, and $b_{n,k}^{II}$, can be obtained in a similar way by replacing $u^{a,n,k}$, $u^{b,n,k}$ with $w^{a,n,k}$, $w^{b,n,k}$ in (A1) to (A6), and solving the following linear equations:

$$\begin{align*}
S_{n,k} Z_{n,k} &= C_{n,k} \\
T_{n,k} Q_{n,k} &= D_{n,k}
\end{align*}$$

(A9)

where

$$\begin{align*}
C_{n,k} &= \begin{pmatrix}
-m_{n} P_{n} (P_{k} - w_{n,k}^{a} P_{k}^{2}) G_{n,k}^{I} / (2 \mu_{r}) \\
0 \\
0 \\
0
\end{pmatrix} \\
D_{n,k} &= \begin{pmatrix}
-m_{n} P_{n} (P_{k} - w_{n,k}^{b} P_{k}^{2}) G_{n,k}^{II} / (2 \mu_{r}) \\
0 \\
0 \\
0
\end{pmatrix}
\end{align*}$$

(A10)

The coefficients, $a_{n,k}^{I}$, $b_{n,k}^{I}$, $a_{n,k}^{II}$, and $b_{n,k}^{II}$, are related with the magnetic field distribution in PM region, and are not concerned in this paper.

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