Design Optimization and Comparison of Linear Magnetic Actuators under Different Topologies

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Abstract: In this study, several types of linear actuators that adopt different permanent-magnet (PM) topologies are studied and compared. These linear actuators are based on the concept of PM magnetic screw transmission, which offers high force density, high reliability, and overload protection. Using different magnetic configurations and assembly methods, these linear actuators are designed and optimized for a fair comparison. Initially, based on the operating principle and maximum thrust force, the surface-mounted magnetic screw is described and optimized. Furthermore, the embedded magnetic screw, Halbach array magnetic screw, and field modulated magnetic screw are investigated and compared. Their electromagnetic performances, such as thrust force, torque, magnetic losses, and demagnetization effects are analytically assessed and verified using finite-element analysis. Finally, a prototype of the surface-mounted magnetic screw is developed to validate the predictions.

Keywords: Linear actuator, magnetic screw, high force, permanent magnet, finite-element analysis

1 Introduction

Linear actuators are receiving increased attention in several applications, such as transportation and aerospace actuation[1-3]. Conventionally, linear motion has usually been achieved using roller/ball mechanical screws, which results in a high thrust force. However, mechanical screws suffer from nonlinear friction and poor operational accuracy[4]. For a variety of linear drive applications, the linear permanent-magnet (PM) motor offers many advantages in terms of maintenance and precision. However, its thrust force density was found to be relatively weak[5-7]. In order to improve the force density, researchers have been focusing on a few novel linear topologies, such as vernier effects and double stator structures. The disadvantages of low power density and manufacturing complexity restricted its development[8-9].

Recently, the concept of magnetic gearing effect has received increased attention and offers high torque density efficiently[10-11]. By extending this idea to a linear actuator, the concept of magnetic screw transmission was proposed[12]. However, it has not gained widespread adoption owing to the poor utilization of magnets in the past, resulting in low energy conversion. With the development of PM materials, and the improvement of topologies, the capability of magnetic transmission has been improving continuously[13-15]. The operating principle of the magnetic screw is similar to a mechanical lead screw, that converts linear motion into rotational motion and vice versa, through the helical magnetic field coupling between the magnetic translator and rotor. Compared with the mechanical lead screw, the non-contact magnetic transmission can alleviate the mechanical jamming caused by the roller/ball. Due to the converted motion, without direct mechanical contact, the magnetic screw transmission exhibits the advantages of high thrust force, inherent overload protection, and high reliability[16-18].

The high-performance magnetic screw, as described in Ref. [19], incorporates the merits of high thrust force density. The magnetic screw constitutes radially magnetized helical shaped PMs, which are surface-mounted, on both the screw and nut. The general framework based on this operating principle has been proposed in this paper and reveals the high force capability of magnetic transmission. However, the
design and manufacturing methods for maximum thrust force optimization have not been considered. In Refs. [20-22], various magnetic screw topologies are described, it is confirmed that several kinds of magnetic screws are also suitable for use in linear actuators owing to the magnetic transmission effects that still apply to these topologies. However, the comparisons, such as electromagnetic performances, costs, and magnetic losses between different topologies is insufficient.

The main drawback of the magnetic screw linear actuator is the process adopted to manufacture the high-performance helical PM poles. The techniques of structure simplification and manufacturing processes are essential to promoting its development. In Ref. [23], the fabrication of the helical PM poles was described in detail. Apart from the thrust force capability and fabrication, magnetic losses and mechanical stress are also significant. Hence, it is essential to investigate and compare the magnetic losses for different PM topologies. In Ref. [24], the magnetic losses and efficiency were investigated and measured, and the efficiency was found to be above 94%. However, this conclusion is unsuitable for application to different topologies of the magnetic screw owing to the losses in the PM and back-iron being closely related to magnetic density and frequency.

The primary objective of this paper is to compare and evaluate the merits and demerits of different magnetic screws for improving electromagnetic performance. More specifically, the various magnetization, magnetic pole topologies, and magnetic field modulation mechanisms are analyzed. Besides, the operating principle for each type of magnetic screw is reviewed as well. Further, a prototype is built to verify the high thrust force density. The rest of this paper is organized as follows. In Section 2, the topologies of the magnetic screw are described. Section 3 evaluates the influence of design parameters and their optimization principles. In Section 4, the electromagnetic performances, such as the thrust force, torque, mechanical stress, magnetic losses, and demagnetization effects of the magnetic screws, are compared. After this, a surface-mounted magnetic screw has been built and tested, and the experimental results are presented in Section 5.

2 Topologies and operating principle

2.1 Surface-mounted magnetic screw

Fig. 1a shows the topology of a 2-pole surface-mounted magnetic screw (SMMS). The SMMS consists of two cylindrical coaxial parts, while the translator moves along its central axis, and the rotor rotates about the same axis. Both the translator and rotor are made of ferromagnetic iron steel yoke and are surface-mounted using radially magnetized helical shaped PMs. The adjacent PMs are radially magnetized in the opposite direction. In the three-dimensional helical PM structure, helical magnetic poles are formed. In order to simplify the calculation, the two-dimensional axisymmetric model shown in Fig. 1b, to verify the axial thrust force, magnetic field distribution, and operational principle, is employed.

The thrust force for the minimum and maximum positions are shown in Fig. 2, respectively. For the minimum thrust force position, the magnetic field distributions are aligned and symmetrical with the rotor and translator. Due to the magnetic field distribution being displaced, the thrust force can be produced using the magnetic field coupling. At the position, as shown in Fig. 2b, the maximum thrust force can be achieved.

2.2 Schematic diagram and magnetic field distributions

According to the operating principle of the magnetic screw, for the 2-pole SMMS, as the rotor completes one rotation, the translator moves one lead,
For example, the lead of the magnetic screw is 20 mm and can convert a translator linear velocity of 1 m/s to a rotor rotary speed of 3 000 r/min. It should be noted that the rotor rotation and translator motion are expressed in different units, namely angle and length, respectively. This is a special gear effect, $G$, and converts rotor rotation into translator linear motion. Considering the power balance between the translator power, $P_t$, and rotor power, $P_r$, the gear ratio of linear velocity, $v$, and rotary speed, $\omega$, would be equal to the ratio of rotor torque, $T_n$, and translator thrust force, $F_t$.

It can be seen that the gear ratio would be defined as $G = \omega/v$. Given the above definition, as the rotor completes one revolution, the translator moves one lead, $\lambda$. Therefore, the gear ratio, $G$, of the magnetic screw can be expressed as

$$G = \frac{\omega}{v} = \frac{2\pi}{\lambda} = \frac{F_t}{T_n} \quad (1)$$

### 2.2 Embedded and Halbach topologies

Hitherto, most researchers have focused on the SMMS. However, to alleviate the magnetic flux leakage and improve mechanical strength, various magnetic screw topologies should be investigated. Fig. 3a shows the topology of the embedded magnetic screw (EMS), which differs in design from the SMMS. The EMS structure employs axially magnetized helical PMs and helical steel rings. The steel ring is sandwiched between two axially magnetized PMs. Therefore, the magnetic fluxes from the axially magnetized PMs are concentrated towards the steel ring. Based on the principle of magnetic circuits, it can be seen that the structure of the PMs and the steel rings have a significant effect on electromagnetic performance. Fig. 3b shows the topology of EMS II, as compared with EMS I. EMS II is more compact and the quantity of PM is much higher. The details of the electromagnetic performances of the EMS are described in Section 4.

Based on the magnetic field distributions of the EMS, the operating principles of EMS I and EMS II are shown in Fig. 4, respectively. Similar to the SMMS, it can be seen that the magnetic field distributions are aligned and symmetrical with the rotor and translator, and the thrust force is zero. With the displacement of the magnetic field, the thrust force is produced. At the position $z_d$, the maximum thrust force can be achieved. In the magnetic field distributions of the EMS, it should be noted that the magnetic leakage has been solved.

To further improve the thrust force density of the magnetic screw, the use of the Halbach PMs array is proposed. Fig. 5 shows the configuration of the Halbach magnetic screw (HMS). It can be seen that four kinds of magnetized PMs are placed on both the translator and the rotor. Due to the adoption of the special PM arrangement, the flux leakage almost disappears and the air-gap magnetic field improves effectively. The electromagnetic performance, such as thrust force density, is consequently enhanced, and the magnetic saturation in the steel-yoke is alleviated. Also, the magnetic field distributions at two typical positions are shown in Fig. 6. It should be noted that the air-gap magnetic flux lines are significantly improved, and the magnetic flux leakage is effectively alleviated.

### 2.3 Field modulated magnetic screw

The concept of a linear magnetic gear, which offers high thrust force density and high reliability, has received increased attention for several applications.
By extending this idea to magnetic screw transmission, the concept of field modulated magnetic screw (FMMS) was proposed, as shown in Fig. 7. It can be seen that the FMMS contains three parts: the outer stator and inner rotor carrying the radially magnetized helical PMs having different numbers of pole pairs. The flux modulator translator consists of helical ferromagnetic pole pieces, which modulate the helical magnetic fields produced by the PMs.

The number of pole pairs of the helical PMs placed on the inner rotor, \( p_i \), and outer stator, \( p_s \), and the number of the helical ferromagnetic pole-pieces, \( n_t \), are related by

\[
n_t = p_r + p_s \tag{2}
\]

For the operating principle of the FMMS, the outer stator rotational speed \( \omega_s = 0 \), \( \lambda \) is the magnetic lead, \( v_t \) is the translator’s linear velocity and \( \omega_r \) is the rotor’s rotational speed. Furthermore, the rotary speed and linear velocity are related by formula (1). Thus, the gear ratio for the FMMS is given by

\[
G = \frac{v_t}{\omega_r} = \frac{T_r}{F_t} = \frac{\lambda}{2\pi} \cdot \frac{p_r}{n_t} \tag{3}
\]

Detection of the helical magnetic field distribution in the airspace using the measured ring is shown in Fig. 8. It can be equivalent to testing the magnetic rings, \( N \) and \( S \), alternately arranged and verifying the flux-modulation effect of the flux modulator on the air-gap flux distribution, excited by nine pole pairs generated by the helical PMs. The adoption of 13 pole pair helical field modulated ferromagnetic pole pieces, results in the 4th and 9th harmonic order, respectively. The 4th harmonic order is the same number of pole pairs as the four pole pair helical PMs placed on the inner rotor screw. Fig. 9 illustrates the flux-modulation effect of the flux modulator on the air-gap flux distribution, excited by the outer stator helical PMs. The design parameters of the FMMS are listed in Tab. 1.

![Fig. 5 Configurations of HMS](image)

The number of pole pairs of the helical PMs placed on the inner rotor, \( p_i \), and outer stator, \( p_s \), and the number of the helical ferromagnetic pole-pieces, \( n_t \), are related by

![Fig. 6 Magnetic field distribution of HMS at different positions](image)

![Fig. 7 Configurations of FMMS](image)

![Fig. 8 Magnetomotive force distribution of helical PMs](image)

![Fig. 9 Flux-modulation effect of flux modulator](image)

| Tab. 1 Design parameter of FMMS |
|---------------------------------|
| **Parameter**                  | **FMMS** |
| Number of pole pairs on inner rotor \( p_i \) | 4       |
| Number of pole pairs on translator \( n_t \) | 13      |
| Number of pole pairs on stator \( p_s \) | 9       |
| Lead \( \lambda/mm \)            | 80      |
| Air-gap length \( g/mm \)        | 1       |
| Magnet remanence \( B_{rem}/T \) | 1.23    |
3 General design and optimization

For a fair comparison, the magnetic screws were designed to have the same overall dimensions and optimization principles. Fig. 10 shows the relevant parameters of the magnetic screw. Firstly, the air-gap, $g$, outer rotor radius, $R_s$, and rotor length, $L_t$, are determined. The optimization process will continue to adjust the amount of PMs, the length of the magnetic lead, and the structure of the magnetic poles, which has a significant effect on electromagnetic performance.

3.1 Surface-mounted magnetic screw

For the SMMS, the PM thickness, $h_p$, and magnetic lead, $\lambda$, are the main parameters, which affect electromagnetic performance, such as volume and thrust force density. The volume of SMMS varies with the PM thickness, $h_p$, and the active volume of the SMMS can be written as

$$V = \pi \cdot (R_s^2 - R_t^2) \cdot L_t$$  \hspace{1cm} (4)

The thrust force density $F_{\text{density}}$ can be expressed as

$$F_{\text{density}} = \frac{F_t}{V} = \frac{F_t}{\pi \cdot (R_s^2 - R_t^2) \cdot L_t}$$  \hspace{1cm} (5)

In Fig. 11, the effect of different PM thicknesses, $h_p$, and variation of magnetic lead, $\lambda$, on thrust force density, $F_{\text{density}}$, is investigated. The magnetic lead, $\lambda$, increases from 10 to 60 mm, and the variation of the PM thickness, $h_p$, is in the range of 1 to 8 mm. It can be seen that when the length of the magnetic lead, $\lambda$, is 20 mm, the highest thrust force density can be achieved. In order to obtain the maximum thrust force, the PM thickness, $h_p$, should be optimized based on the fixed magnetic lead, $\lambda$. As the $h_p$ increases, the thrust force also increases. However, due to the saturation of the airspace, the thrust force rises to a certain point. Hence, based on the considerations of high electromagnetic performance, the magnetic lead, $\lambda$, and PM thickness, $h_p$, are chosen to be 20 and 6 mm, respectively. The detailed design parameters for the SMMS are listed in Tab. 2. Moreover, other magnetic screws are referenced to these basic parameters.

![Fig. 10  2-D model with design parameters](image)

![Fig. 11  Optimization of the SMMS](image)

| Parameter | Value |
|-----------|-------|
| Outer radius of rotor $R_s$/mm | 36 |
| Outer radius of translator $R_m$/mm | 24 |
| Inner radius of translator $R_r$/mm | 13 |
| Magnetic lead $\lambda$/mm | 20 |
| Translator length $L_t$/mm | 60 |
| Length of air-gap $g$/mm | 1 |
| Thickness of PM $h_p$/mm | 6 |
| Thickness of steel yoke $h_t$/mm | 5 |
| Magnet remanent $B_{\text{rem}}$/T | 1.2 |

3.2 Embedded and Halbach topologies

In the embedded magnetic screw (EMS), the magnetic fluxes produced by the axially magnetized PMs are concentrated towards the helical-shaped steel rings and based on the operating principle of the magnetic reluctance variation forming a helical-shape magnetic pole. The structure of the steel rings and axially magnetized PMs will affect the electromagnetic performance. Thus, the length of the embedded PM, $l_p$, and steel ring tooth, $l_t$, need to be optimized. The details pertaining to the size of the EMSs are described in Fig. 3.

For EMS I, the variation of the thrust force with
the length of the embedded PM is as shown in Fig. 12a. It can be seen that as the length of the PM increases, the thrust force increases, up to the peak value when the length of the PM is 7 mm, and then decreases due to the saturation in the steel ring. In Fig. 12b, the influence of the length of the tooth, \( l_{t1} \), on thrust force is investigated. The thrust force reaches a maximum value when the length of the tooth is 5 mm. In EMS II, the structure of the PM varies with the structure of the steel ring tooth. The influence of the length of the tooth, \( l_{t2} \), on the thrust force, is as shown in Fig. 12c, when the length of the tooth is 4 mm, the maximum thrust force is achieved.

To improve the thrust force of the magnetic screw further, the Halbach magnetic screw (HMS) is optimized. For the HMS, the length of different magnetized PMs will significantly affect force performance. The length of radially magnetized PM, \( l_r \), is the main contributor to the thrust force, which is illustrated in Fig. 5. Fig. 12d shows the variation in the thrust force with the length of the radially magnetized PM. It should be noted that the appropriate length of the radially magnetized PMs will improve the force performance efficiently. Due to the fixed magnetic lead, \( \lambda \), the length of axially PM varies with the length of the radial PM. The length of the radially magnetized PM varies from 3 to 9 mm, and when the length of the radially magnetized PM is 5.5 mm, the maximum value of thrust force can be achieved.

### 3.3 Field modulated magnetic screw

The FMMS is designed to have the same overall dimensions as the other magnetic screw, and the quantity of its PMs is the same as that for SMMS. For the FMMS, the thickness of the PM and ferromagnetic pole-pieces should be optimized based on the fixed lead, \( \lambda \). Fig. 13a shows the optimization of the PM thickness. In the inner rotor part, the thickness of the rotor PM varies from 1 to 5 mm, the thrust force reaches its maximum value and then drops. This is because of the effect of saturation on the rotor steel yoke and airspace. The same optimization principle is employed in the outer stator part. Based on the high-performance design, the thickness of the rotor PM and stator PM are selected to be 3 and 4 mm, respectively. In addition, the thickness of the ferromagnetic pole has a significant effect on the thrust force. Fig. 13b shows that the thrust force affected by the thickness of the ferromagnetic pole, which is chosen to be 2 mm.
In this section, various kinds of magnetic screws, based on the same overall dimension and operation conditions, will be evaluated and compared. Their key design dimensions and parameters are listed in Tab. 3. It can be seen that the external dimensions of all magnetic screws are the same and the material properties of the magnet and steel ring are consistent. This is a prerequisite for a fair comparison.

### Tab. 3 Parameter comparison

| Parameter          | SMMS | EMS I | EMS II | HMS  | FMMS |
|--------------------|------|-------|--------|------|------|
| Outer diameter/mm  | 72   | 26    | 20     | 20   | 80   |
| Inner diameter/mm  | 20   | 20    | 20     | 20   | 20   |
| Rotor length/mm    | 60   | 60    | 60     | 60   | 60   |
| Air-gap length/mm  | 1    | 1     | 1      | 1    | 1    |
| Magnetic lead/mm   | 10   | 10    | 10     | 10   | 10   |
| Pole-pitch/mm      | 10   | 10    | 10     | 10   | 10   |
| Magnet mass/kg     | 1.17 | 0.82  | 0.96   | 1.17 | 1.17 |
| Iron mass/kg       | 0.95 | 0.41  | 0.24   | 0.95 | 2.53 |
| PM remanence/T     | 1.23 |       |        |      |      |
| Magnet material    | Nd-Fe-B |     |        |      |      |
| Steel material     | DT4C |       |        |      |      |

### 4.1 Thrust force and torque

The results of the thrust force are illustrated in Fig. 14a. It can be seen that the HMS exhibits a significant improvement in the thrust force performance. The thrust force of the HMS is 47.8% higher than that of the SMMS. It can be observed that by adopting the Halbach PM arrays, the thrust force can be improved effectively. The maximum thrust force of the HMS is 4.36 kN, which offers the highest thrust force capability. In addition, the EMS II has more advantages than the EMS I with regards to obtaining a higher thrust force. It should be noted that the thrust force of the EMS II is 45.3% higher than that of EMS I. This is because the amount of PM in the EMS II is higher, resulting in a higher air-gap flux density. Fig. 14b depicts their torque results, which can verify the results of the thrust force. Meanwhile, using formula (1), the relationship between the thrust force, $F_t$, and torque, $T_n$, can be verified.

Fig. 15 shows the electromagnetic performance of the FMMS. The results of the field modulation MMF space harmonic in the air-gaps is as shown in Fig. 15a. The flux-modulation effect of the flux modulator, which modulates the magnetic fields produced by the helical PMs placed on the rotor and stator respectively are measured. It can be seen that the MMF space harmonic can verify the operating principle of the FMMS and this result confirms that the assumption of the field modulation effect in the magnetic screw is acceptable.

The relationship between torque and thrust force is illustrated in Fig. 15b. The thrust force reached a value of 3.38 kN, and the torque of the inner rotor screw is 13.5 N·m, and when the rotated speed of the inner rotor screw is 300 r/min, the translator travels at 0.13 m/s. Meanwhile, the thrust force, $F_t$, and torque, $T_n$, and transmission ratio in formula (3) has been confirmed, which satisfies the modulation ratio. The major performance comparisons for all magnetic screws are summarized in Tab. 4.
Apart from the thrust force and torque, the magnetic losses are also essential characteristics of the magnetic screws. This section will compare and analyze the losses of the magnetic screws under the same operating conditions. The magnetic losses of the magnetic screws are mainly composed of PMs and back-irons, caused by a varying magnetic field. The losses for each part of the magnetic screws with translator speeds of 1 m/s are shown in Fig. 16a. It can be observed that the PM losses are the main components of the total losses. In comparison with the conventional magnetic screws, the FMMS has more harmonics in the air-gaps, and thus the magnetic loss is much higher. In the EMS, since the PMs are embedded into the back-iron, thus the PM loss is reduced. In the HMS, the effect of PM segmentation on PM loss reduction is noticeable. Due to the Halbach magnetized array, the magnetic field distribution in iron-yoke can be alleviated effectively, resulting in lower iron loss. Fig. 16b shows the variation in PM losses with translator speed. It can be seen that with the increase in the translator speed, the PM losses of the magnetic screws are significantly increased.

4.3 Mechanical stress analysis

The mechanical stress analysis is performed to check the durability of different types of linear actuators, and the 3-D finite element analysis is performed using the ANSYS Workbench software. Fig. 17 shows the mechanical stress analysis of the different structures of the linear actuators under full load conditions. It can be seen that the maximum mechanical stress for the SMMS, EMS I, EMS II, and HMS is 8.12, 1.81, 5.03, and 13.2 MPa, respectively. These values are much smaller than the tensile strength of the magnet and steel material. Based on the same analysis methodology, the mechanical stress of the proposed helical ferromagnetic translator is given, and the maximum value is 31.4 MPa. Therefore, it can be considered that all magnetic screws are within the safe range of mechanical stresses.

4.4 Demagnetization

The above magnetic screws employ high performance sintered Nd-Fe-B PM materials. It is necessary to investigate the magnet demagnetization. The irreversible demagnetization occurs when the operating point of the magnet drops below the knee point of its $B$-$H$ characteristic. Fig. 18 shows demagnetization of the PM in the SMMS. Based on the fixed translator magnet thickness of 6 mm, the rotor PM thickness

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**Tab. 4 Performance comparison**

| Parameter                  | SMMS | EMS I | EMS II | HMS   | FMMS |
|----------------------------|------|-------|--------|-------|------|
| Rotor speed/(r/min)        | 300  | 0.10  | 0.10   | 0.10  | 0.13 |
| Linear speed/(m/s)         | 0.10 | 0.10  | 0.10   | 0.10  | 0.13 |
| Thrust force/kN            | 2.67 | 2.32  | 3.68   | 4.35  | 3.38 |
| Torque/(N·m)               | 8.28 | 7.38  | 11.51  | 13.55 | 13.50|
| Force density/(MN/m³)      | 12.6 | 10.9  | 17.3   | 20.5  | 11.5 |

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**Fig. 15** Characteristics of the proposed FMMS

**Fig. 16** Magnetic losses

**Fig. 17** Mechanical stress analysis

**Fig. 18** Demagnetization
varies. It can be observed that the thinner magnets are more prone to demagnetization. In order to prevent demagnetization, the thickness of the magnet on the rotor, and the translator must be equal to ensure balance.

Fig. 17 Mechanical stress of different kinds of linear actuators

(a) SMMS
(b) EMS I
(c) EMS II
(d) HMS
(e) FMMS

Fig. 18 Demagnetization of PMs at different thickness

(a) 3 mm
(b) 4 mm
(c) 5 mm
(d) 6 mm
(e) Scale

Fig. 19 Flux density distribution and demagnetization of EMS

Fig. 19 shows the magnetic field distributions of the EMS. It can be observed that the powerful magnetic flux is focused on the steel rings. Therefore, the irreversible demagnetization of the PM must be considered, as shown in Fig. 19a. Partially irreversible demagnetization occurs in EMS II at the position of the maximum thrust force. Fig. 19b illustrates the partial demagnetization region.

Fig. 20 Method to form the segmented PM

To simplify manufacturing, the segmented magnet structure is proposed. The proposed method to approximate the ideal helical magnetic pole is illustrated in Fig. 20. Considering the radial magnetization technology, the PM arc is selected to be 45°. A normal 45° PM block is shown in Fig. 20a and its side view is shown in Fig. 20b. In order to obtain a nearly ideal helical magnetic pole, the two side surfaces of the 45° PM arc are cut with an appropriate angle with respect to the top and bottom edges, as shown in Fig. 20c.

The SMMS prototype is processed, as shown in Fig. 21. It can be seen that an approximately ideal helical magnetic pole is formed, and the surface-roundness is excellent. The SMMS consists of two parts, a translator and a rotor. Both translator and rotor are made of ferromagnetic iron steel yoke and surface-mouted using radially magnetized helical shaped PMs. The schematic of the magnetic screw experimental platform setup is shown in Fig. 22.

The thrust force characteristic of the SMMS is measured experimentally. Based on the operating principle of the magnetic screw, the rotational speed of
the rotor is 30 r/min, resulting in the translator’s linear velocity of 0.01 m/s. The value of the thrust force is measured, as shown in Fig. 23a. At the position of half a pole-pitch ($z_d = \tau_p/2$), the maximum thrust force can be achieved. It should be noted that the 3-D FE results are in excellent agreement with the value of the measured results. The measured thrust force is about 9% lower than in the case of the 2-D FE result, which is mainly due to the effect of manufacturing tolerance and friction. The high thrust force in the SMMS has been verified. Moreover, the relationship between the linear displacement and rotary angle is measured, as shown in Fig. 23b. It can be seen that this relationship is approximately linear and agrees with the predicted values.

6 Conclusions

In this paper, several magnetic screws with different topologies have been presented and compared. Their electromagnetic performances, such as thrust force, torque, magnetic losses, and demagnetization effects, are analytically assessed and verified by means of simulation. By adopting the magnetic screw transmission, high thrust force density can be achieved. The HMS has an excellent advantage in improving thrust force. The concept of FMMS is particularly suited for long output stroke and high thrust force requirement applications. In addition, the experimental results of the SMMS prototype verify the thrust force of the magnetic transmission.

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