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Novel tubular switched reluctance motor with double excitation windings: Design, modeling, and experiments

Liang Yan,^{1,2,a} Wei Li,¹ Zongxia Jiao,¹ and I-Ming Chen³

¹School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China

²Shenzhen Institute of Beihang University, Shenzhen 518057, China

³School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

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The space utilization of linear switched reluctance machine is relatively low, which unavoidably constrains the improvement of system output performance. The objective of this paper is to propose a novel tubular linear switched reluctance motor with double excitation windings. The employment of double excitation helps to increase the electromagnetic force of the system. Furthermore, the installation of windings on both stator and mover can make the structure more compact and increase the system force density. The design concept and operating principle are presented. Following that, the major structure parameters of the system are determined. Subsequently, electromagnetic force and reluctance are formulated analytically based on equivalent magnetic circuits, and the result is validated with numerical computation. Then, a research prototype is developed, and experiments are conducted on the system output performance. It shows that the proposed design of electric linear machine can achieve higher thrust force compared with conventional linear switched reluctance machines. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4938092>]

I. INTRODUCTION

Electric linear machine is a device that converts electrical energy into linear mechanical energy directly.^{1–6} It has great potential applications in machining tools, precision drive systems, transportation, and so on. Although many works have been done on permanent magnet (PM) electric machines,^{7–10} linear switched reluctance motor (LSRM) is one of the hot research topics due to its simple structure, high reliability, and low cost. For example, Lee *et al.*¹¹ proposed a standard design procedure for a single-sided and longitudinal flux based linear switched reluctance machine that consists of six translator poles and nine stator poles. Lee *et al.*¹² proposed two-phase switched reluctance machine (SRM) with a stator composed of E-core structure having minimum stator core iron. The air gap around the common stator pole has constant and minimum reluctance irrespective of rotor position through its unique design. Darabi *et al.*¹³ compared longitudinal flux LSRM with transverse flux one and presented that longitudinal flux LSRM produces greater attractive force and needs less amount of steel in the secondary. Pan *et al.*¹⁴ proposed a double-sided electric asymmetric LSRM. This machine structure helps to achieve alleviation of motor saturation magnetization effect and high thrust force output. Lobo *et al.*¹⁵ presented the comparison of four LSRMs as possible candidates for application in vertical elevators, i.e., single-sided LSRM, double stator LSRM, double stator LSRM with an inner stator, and double stator LSRM with a different translator. However, the force output of conventional flux-switching linear motor is relatively low. The major reason is that the magnetic flux density in air gap is not high enough, which in turn influences the force output

significantly. As a result, hybrid operating principle based on excitation of flux-switching and permanent magnets has been proposed by researchers. For instance, Seok *et al.*¹⁶ presented a $\pi/4$ -multiple-coupled two-phase linear hybrid stepping motor. It can achieve low cogging force due to its special structure, and yet low thrust force. Hwang *et al.*¹⁷ proposed a hybrid excited linear flux switching PM motor with DC excited windings on mover. It can improve the performance of thrust force and speed, but the DC excited winding patterns reduce the electrical efficiency and increase mover inertia. Jin *et al.*¹⁸ proposed a PM flux-switching linear machine. The magnets with alternate polarity are sandwiched between slotted mover cores where the windings are accommodated, and half-amount of the magnets used in the conventional machine are replaced with flux barriers. Wang *et al.*¹⁹ developed a three-phase flux-switching PM motor with relatively high force ripple. Kwok *et al.*²⁰ designed a two-dimensional motor to replace the conventional X-Y table with a relatively simple and robust structure. Cao *et al.*^{21–23} proposed a complementary and modular linear flux-switching permanent magnet motor. It has relatively high output force, and its back electromotive force has sinusoidal characteristics. The modular design facilitates process and maintenance and achieves strong fault tolerance and ease of control. The permanent magnet poles are difficult to install and possibly be affected by coils thermal, which may reduce the system reliability significantly and is unacceptable for aerospace applications. Li *et al.*²⁴ proposed a linear variable machine equipped with a set of field winding capable of adjusting the air-gap flux. It is excited by both armature winding and field winding, by inviting the DC field winding. The proposed machine not only has the flux control capability but also realizes the bipolar operation. But this winding mode may lead to the waste of the stator slot space and low force density.

^aAuthor to whom correspondence should be addressed. Electronic mail: lyan1991@gmail.com

The objective of this paper is to propose a novel tubular linear switched reluctance motor with double excitation windings on both stator and mover. The double excitation benefits the force improvement of electric linear machine. The arrangement pattern of windings on stator and mover helps to achieve compact system structure and high thrust density. The rest is organized as follows. In Section II, the schematic structure and operating principle of the proposed machine are presented. The major parameters are determined in Section III. Formulation of force output and reluctance is conducted in Section IV. A research prototype and experimental works are presented in Sec. V. The paper is concluded in Section VI.

II. CONCEPT DESIGN AND OPERATING PRINCIPLE

A. Concept design

The schematic structure of the proposed tubular linear switched reluctance motor with double excitation is shown in Fig. 1. Two sets of windings are mounted on both stator and mover to generate magnetic flux loops in the system. The stator windings are used to generate the primary field, and their exciting mode determines the working status of the motor. In each stator slot, there are two annular coils marked with different colors. In other words, two annular coils are mounted on both sides of each stator tooth. Energizing both coils under control can help to enhance the flux density in the stator teeth and thus to improve the force output of the linear machine. The mover windings produce the secondary field. The employment of mover windings helps to enhance the output performance of machine system to generate continuous linear motions and higher thrust density. The mover always intends moving to a position with minimum reluctance of air gaps. Thus, the variation of current input can produce reciprocating motions of the mover. Because the windings are installed on both stator and mover, the machine volume is utilized with high efficiency compared with conventional reluctance switch machines, which may increase the system force density and working efficiency. The double excitation and ferromagnetic materials such as iron cores are employed to improve the force output further. Each phase has two

FIG. 1. Schematic structure of the tubular linear switched reluctance motor with double excitation windings.

FIG. 2. Operating principle of tubular linear machine with double excitation windings. (a) The mover translates to the left side and (b) the mover translates to the right side.

working pole pairs of stator and mover. Eight stator teeth align with six mover teeth. The stator consists of multiple segments to facilitate the assembly of windings. Due to the axially symmetric structure, the radial force is nearly equal to zero, which in turn helps to reduce the mover friction significantly.

B. Operating principle

The operation of tubular LSRM with double excitation windings follows the principle of minimum reluctance. As shown in Fig. 2(a), the windings on both sides of teeth 2 and 6 of the stator are energized, and the inner-side windings of mover teeth 2 and 5 are energized too. Magnetic flux is thus produced along stator teeth 6, 2 and mover teeth 2, 5, and forms a closed loop. To minimize the air gap reluctance in the magnetic flux loop, the mover produces motion toward the left side. Similarly, when energizing the windings on both sides of stator teeth 4 and 8, and inner-side windings of mover teeth 3 and 6, the magnetic flux loop between the stator and

FIG. 3. Output performance of different pole pairs when only one set of stator and mover windings are energized.

FIG. 4. Major structure parameters of the proposed LSRM.

mover is produced. The mover thus translates towards the right side to minimize the air gap reluctance of the machine system. Therefore, by varying the current inputs in the stator and mover windings, the reciprocating linear motions in both directions can be achieved.

III. STRUCTURE DESIGN OF LINEAR MACHINE

A. Determination of stator and mover pole pairs

Pole pair number is an important factor that influences system output performance of electric linear machines. Generally, 8-6 or 12-10 stator and mover pairs are used for design of electric linear machines. Numerical computation is conducted on the thrust output of the proposed linear machine with either 8-6 or 12-10 pole pairs. Figure 3 shows that 8-6 LSRM has larger output force than 12-10, because it has more turns of windings in the same overall system dimensions. Smaller pole-pair number could also be chosen for the machine design but may generate large output force ripple and compromise continuous motions of the mover. Therefore, 8-6 pole pair number is chosen in this study.

B. Determination of major structure parameters

The determination of structure parameters has significant influence on the motor output performance. The major parameters of the proposed linear machine include motor length L , stator diameter D , mover diameter d , air gap g , width of stator pole w_1 , width of mover pole w_2 , depth of stator slot τ_s , and depth of mover slot τ_m as illustrated in Fig. 4.

The motor length and diameter have the relationship of

$$\lambda = \frac{L}{D}. \quad (1)$$

λ has significant impact on motor output performance. Large value of λ can benefit the thrust improvement, but may compromise the system heat dissipation. In general, electric motor can achieve better output performance when $\lambda = 0.5-5.0$. In this study, λ is selected as 4.5. Air gap is another important parameter for electric linear machines. Generally, small air gap is preferred for the structure

FIG. 5. Output performance of LSRM with different structure parameters.

TABLE I. Major parameters of the proposed linear motor.

Parameters	Value
Phase number	4
Pole pair number (N)	8-6
Motor length (L)	240 mm
Motor diameter (D)	100 mm
Tooth width (W)	10 mm
Mover slot depth (τ_m)	8 mm
Stator slot depth (τ_s)	16 mm
Mover diameter (d)	16 mm

design of switched reluctance linear motor. To facilitate the manufacturing and system assembly of the linear machine, the size of air gap, g , is selected as 1 mm.

To ensure the continuous force output and smooth motion of the mover, the widths of stator and mover tooth, w_1 and w_2 , are equal. Ignore the flux leakage of the linear motor, the area of the stator pole is expressed as

$$A_s = \frac{D}{2} L k_s, \quad (2)$$

where k_s is the correction factor. In general, $k_s = 0.85$ – 1.0 . The width of stator pole, w_1 , is thus determined as

$$w_1 = \frac{A_s}{L} = \frac{D}{2L} L k_s = \frac{D}{2} k_s. \quad (3)$$

Similarly, the mover pole width w_2 can be expressed as

$$w_2 = \frac{A_m}{L} = \frac{D}{2L} L k_m = \frac{D}{2} k_m, \quad (4)$$

where $k_m = 0.3$ – 1.0 . The depth of stator slot is related to motor diameter and stator yoke height. The minimum size of stator yoke is restricted to ensure that stator yoke is not saturated when motor is under maximum flux density. The depth of stator slot is calculated as

$$h_1 = \frac{D}{2} - \frac{d}{2} - (1.2-1.4) \frac{w_1}{2}. \quad (5)$$

Similarly, the depth of mover slot is expressed as

$$h_2 = \frac{d}{2} - (1.2-1.6) \frac{w_2}{2}. \quad (6)$$

Finite element method is used for numerical computation to simulate the relationship between thrust output and structure parameters such as w_1 , d , and τ_m . The result is presented in Fig. 5. It shows that the tubular linear machine can achieve maximum output force when the major parameters take the values in Table I. Smaller thrust output or magnetic saturation may happen in LSRM for other parameter values.

IV. FORMULATION OF FORCE OUTPUT

A. Models of equivalent magnetic circuit

The following assumptions are made to facilitate the study of theoretical modeling.

1. There is no eddy current on the stator and mover.
2. Hysteresis in stator and mover are negligible except the teeth.
3. Temperature has no significant influence on the flux distribution.
4. Mutual inductance is negligible under DC excitation.

The mathematical model of the force output of the proposed LSRM can be derived with equivalent magnetic circuit^{25–27} as follows. The magnetic reluctance of air gap in the linear machine is calculated from geometrical dimensions and magnetic permeability as

$$R = \frac{Hl}{BA} = \frac{l}{\mu A}, \quad (7)$$

where μ is the magnetic permeability that can be calculated from magnetic flux density B and magnetic field intensity H , l is the length of the magnetic path, and A is the sectional area crossed by the magnetic flux. According to Ampere's circuit law, the magnetomotive force can be written from magnetic circuit in the following form:

$$F_l = NI = \oint \vec{H} \cdot d\vec{l} = \sum_i H_i l_i. \quad (8)$$

With the combination of Eqs. (7) and (8), magnetic flux of the circuit is thus obtained as

$$\Phi = \frac{F_l}{R} = \frac{NI\mu A}{l}. \quad (9)$$

FIG. 6. Equivalent circuit model with single working phase.

Eq. (9) presents the relationship between the input current and the magnetic field strength in the electromagnetic machine.

B. Calculation of reluctance

Figure 6 presents the equivalent circuit model of the proposed LSRM based on Equivalent magnetic circuit (EMC) method. Only single phase working model is presented for ease of understanding. All phase windings have similar arrangement. To obtain accurate theoretical model of thrust

output, the reluctance must be accurately calculated. The ferromagnetic materials near the stator and mover tooth are often in magnetic saturation, and flux linkage can be expressed as a nonlinear function of phase current and rotor position. It is generally challenging to calculate the reluctance. Therefore, this study proposes a modeling approach to obtain the magnetic reluctance precisely.

According to the system operating principle, the reluctance of the proposed LSRM always varies between the maximum and minimum values. Figure 7 shows the flux linkage when stator is at some specific position under the mover coordinate system. Assume that the stator is at the initial position of $Z = 0$ as shown in Fig. 7(a) and then moves to subsequent positions at $Z = 5$ mm, 10 mm, 15 mm, and 20 mm in Figs. 7(b)–7(d). The windings are excited with the same current input for all positions. The proposed LSRM has maximum average air gap and minimum flux linkage at $Z = 0$. With the increase of Z , the average air gap gradually decreases, and flux linkage increases. At $Z = 20$ mm, the average air gap reaches the minimum value, and flux linkage reaches the maximum value. To obtain the air gap reluctance precisely, the working process and flux distribution of the tubular linear motor are anatomized.²⁸ First, when the mover is at the position between $Z = 10$ mm and $Z = 20$ mm, the air gap magnetic field is divided into several regions as shown in Fig. 8(a). The reluctance of region 1 can be calculated from Eq. (7) directly. Due to the symmetric arrangement of regions 2 and 3, the reluctance computation of these two regions is similar. In subsequent study, only the reluctance of region 2 is analyzed. The same approach can be applied to region 3. It is important to point out that the thrust force is mainly generated by the flux linkage of regions 2 and 3, because the direction of electromagnetic force depends on the flux linkage. Specifically, the flux linkage of region 1 is in radial direction, and thus this part of flux linkage generates radial force. In contrast, the flux linkage direction of regions 2 and 3 tilts a certain degree from the motor axis, and thus, it generates both thrust force and radial force.

Assume that l_Z is the magnetic circuit length of air gap when flux linkage is at the position of $Z \in [m, n]$. The magnetic conductance of region 2 is

$$P_2 = \frac{1}{N^2} \int_m^n \frac{N_Z^2}{l_Z} dZ, \quad (10)$$

where N_Z represents flux linkage contained in magnetic circuit unit, and N represents pole winding turns. In general, N_Z is a quadratic trinomial function with respect to Z , and l_Z is a binomial function with respect to Z . Each region has different values of N_Z and l_Z . As a result, the analytical formula of magnetic conductance is different. In order to simplify the calculation process, a comprehensive coefficient K is employed, and then, Eq. (10) can be represented as following:

$$P_2 = K \int_m^n \frac{(a + bZ + cZ^2)^2}{d + eZ} dZ. \quad (11)$$

The integrand numerator in Eq. (11) is a polynomial function. Given the definition of coefficients in the polynomial as $c_0 = a^2$, $c_1 = 2ab$, $c_2 = 2ab + b^2$, $c_3 = 2bc$, and $c_4 = c^2$.

FIG. 7. Flux linkage distribution of the linear motor with mover's positions at (a) $Z = 0$ mm, (b) $Z = 5$ mm, (c) $Z = 10$ mm, (d) $Z = 15$ mm, and (e) $Z = 20$ mm.

FIG. 8. Region division of air gaps for analysis of magnetic field distribution.

In general, $e \neq 0$, $d \neq 0$, and $f_0 = \frac{\ln(d+ex)}{e}$. The iterative computation can be expressed as

$$f_i = \frac{1}{e} \left(\frac{x^i}{i} - df_{i-1} \right), i = 1, 2, 3, 4. \quad (12)$$

Therefore, the magnetic conductance is

$$P_2 = K \sum_{i=0}^4 [f_i(n) - f_i(m)]. \quad (13)$$

In particular cases, when $d \neq 0$, $e \neq 0$, and $a = 0$, the magnetic conductance is rewritten as

$$P_2 = \frac{K}{e} \sum_{i=0}^4 \frac{c_i}{i} (n^i - m^i). \quad (14)$$

When $d \neq 0$, $e \neq 0$, and $a \neq 0$, it is

$$P_2 = \frac{K}{e} \left[c_0 \ln \frac{n}{m} + \sum_{i=0}^4 \frac{c_i}{i} (n^i - m^i) \right]. \quad (15)$$

And when $e = 0$ and $d \neq 0$, it is

$$P_2 = \frac{K}{d} \sum_{i=1}^5 \left[\frac{c_{i-1}}{i} (n^i - m^i) \right]. \quad (16)$$

Thus, the air gap reluctance for every region is calculated as

$$\begin{cases} R_{g1} = \frac{g}{\pi d(m - Z_1)\mu} \\ R_{g2} = R_{g3} = \frac{1}{P_2} \\ R_g = \frac{1}{P_1 + P_2 + P_3} \end{cases} \quad (17)$$

C. Formulation of thrust force output

To facilitate the winding assembly, modular design is utilized for the stator and mover. One single stator module is presented in Fig. 9. The stator module includes a hole at the center. The mover goes through it and produces reciprocating motions. The ring-shaped stator coils are mounted in the

FIG. 9. Stator module of the proposed LSRM.

FIG. 10. Electromagnetic force generated by one phase of the proposed machine.

FIG. 11. Electromagnetic force of the machine when all phase windings are energized.

module and encircle the mover. The fringe is connected to the neighboring stator modules with similar structure. However, the air gap exists in between the modules more or less, which unavoidably influences the precision of mathematical models. To improve the precision, we propose two reluctance components of air gaps, R_{sg} and R_{mg} , as shown in Fig. 6, for the stator and the mover, respectively. According to Eq. (8), the magnetic circuit flux can be obtained from

$$\Phi = \frac{F_l}{R} = \frac{2NI}{5R_{sg} + 2R_{mg} + R_g}, \quad (18)$$

FIG. 12. Relationship between thrust and number of energized mover windings.

FIG. 13. Relationship between thrust and number of energized mover windings.

and the magnetic potential of air gap can be calculated from

$$U_g = \Phi R_g = \frac{2NIR_g}{5R_{sg} + 2R_{mg} + R_g}. \quad (19)$$

Thus, the flux of region 2 is

$$\phi_{g2} = U_g / R_{g2} = \frac{2NIR_g}{(5R_{sg} + 2R_{mg} + R_g)R_{g2}}. \quad (20)$$

The magnetic energy is accordingly

$$W_{r2} = \int_0^I \phi_{g2} dI = \int_0^I \frac{2NIR_g}{(5R_{sg} + 2R_{mg} + R_g)R_{g2}} dI. \quad (21)$$

The electromagnetic force generated by region 2 can be calculated from

$$F_e = \frac{\partial W_{r2}}{\partial l_z}. \quad (22)$$

Due to the inclination angle between the electromagnetic force and the Z axis, a correction coefficient is used to calculate the thrust force, i.e.,

$$F = 4\kappa \frac{\partial W_{r2}}{\partial l_z}. \quad (23)$$

FIG. 14. Research prototype of the proposed LSRM.

FIG. 15. Test platform for motor thrust force and phase inductance.

Generally, κ is equal to $1/\sqrt{2}$. The above computation is available when the mover is at $Z = 0$ to $Z = 10$ mm. Fig. 8(b) shows the regional division of the air gap. Although the position of region 1 is a bit different, the total reluctance of all regions follows the same calculation, and thus, the same expression of thrust force output can be obtained. The coefficient κ is not a constant any more. It is associated with the mover position as

$$\kappa = \frac{g}{\sqrt{g^2 + (Z + 1)^2}}. \quad (24)$$

The electromagnetic force generated by one phase of the proposed machine is shown in Fig. 10. Numerical computation is conducted and compared with the analytical models. It indicates that the analytical model fits with the numerical results well. The developed mathematical model of thrust output could be employed for real time motion control of the linear machine. Figure 11 presents the electromagnetic force of the linear machine when all phase windings work simultaneously. We can find that the output force curve is approximately a sine wave, and the thrust value fluctuates between 220 N and 290 N. Employment of multi-phase windings can help to reduce the force ripple.

FIG. 16. Comparison of thrust forces by FEM and experimental result.

D. Inductance calculation

The inductance of the proposed linear machine is calculated. The total flux linkage and phase inductance have the following relationship:

$$\Phi = LI. \quad (25)$$

The phase inductance can be obtained with Eq. (18) as

$$L = \frac{\Phi}{I} = \frac{2N}{5R_{sg} + 2R_{mg} + R_g}. \quad (26)$$

V. NUMERICAL SIMULATION AND EXPERIMENTS

A. Numerical simulation

Numerical computation is conducted to simulate the thrust output of the proposed linear machine with double excitation. Fig. 12 presents the relationship of thrust output and mover positions with different number of energized windings. It shows that increasing the number of energized mover windings can significantly improve the output performance of the linear machine, because much more local magnetic linkage is produced. Figure 13 shows the induced voltage of stator and mover windings when the mover moves at the speed of 1 m/s. It shows that the induced voltage of mover winding curve is smoother than stators induced voltage. The mover winding could be used for position sensing in the future.

B. Development of research prototype

A research prototype of the proposed LSRM has been developed as shown in Fig. 14. In order to improve electromagnetic force output, ferromagnetic material is used for the machine fabrication. Eight modules are used for the stator design for the ease of winding assembly. Two linear bearings are utilized to support the mover on the two ends.

FIG. 17. Comparison of stator phase inductance by analysis result and experimental result.

Rows of tiny balls are embedded in the inner wall of the bearing to support the mover. The friction on the mover can thus be reduced significantly. According to the movers diameter, the bearings with inner diameter of 16 mm and outer diameter of 28 mm are selected for the machine design. The linear machine is mounted on one base that in turn is fixed on the testing platform. The current input can be supplied into the mover windings and the stator windings simultaneously to generate high force output of the linear machine.

C. Testing platform and experimental investigation

The testing platform is developed as shown in Fig. 15 for experimental study on the electric linear machine. One sensor is mounted on the end of mover to measure the thrust output of linear machine. One phase windings on the stator and the mover are energized to generate force output with respect to different mover positions. The experimental result is shown in Fig. 16. It shows that the measured thrust force fits with FEM result well, and the experimental result is slightly smaller than the simulation result, which might be caused by the machining and assembly error of windings, etc.

Experiments on inductance are also conducted. Figure 17 presents the stator phase inductance of the proposed LSRM with respect to the mover position. It can be seen that the analytical result agrees with the experimental result well. The analytical model can be used for motion control of the tubular linear machine in the future.

VI. CONCLUSION

The objective of this paper is to propose a novel tubular linear switched reluctance motor with double excitation. The two sets of windings on the stator and mover help to improve the force output and make the linear machine more compact as the design space of the linear machine is utilized with high efficiency. The thrust output and inductance are formulated analytically. The magnetic flux distribution in the air gap with respect to different mover positions is analyzed, and region division method is proposed to improve the modeling precision. Numerical computation is carried out to validate the proposed design. A research prototype and an experimental

testbed have been developed, and experiments are conducted on the force output and inductance. It shows that the analytical models fit with experimental results well, and the proposed linear machine design helps to improve the system output performance.

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