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DESIGN OPTIMIZATION OF A THREE PHASE TUBULAR LINEAR SWITCHED RELUCTANCE ACTUATOR

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ABSTRACT

This paper presents the design and optimization of tubular Linear Switched Reluctance Actuator (LSRA) without permanent magnet that has 12:8 stator-to-mover pole pairs ratio. The performances between 6:4 and 12:8 stator-to-mover pole pairs ratio tubular LSRA are compares in term of the generated thrust force. At the same excitation current, the generated thrust force of tubular LSRA with 12:8 stator-to-mover pole pairs ratio found to be more than three times as that of 6:4 stator-to-mover pole pairs tubular LSRA. In order to obtain the optimum performance of the proposed tubular LSRA, the design optimization and the influence of tooth width and mover tooth height on generated thrust force are analyzed and computed using commercial 3D Finite Element Method (FEM) analysis software (Maxwell 3D Version 17.0). The results shows that the proposed actuator with optimized design parameters generates the maximum output thrust force for approximately 2.05 N when 3 A excitation current is applied.

Keywords: tubular LSRA, stator-to-mover pole pairs, finite element analysis, thrust force.

1. INTRODUCTION

Linear actuators directly convert electrical energy into linear mechanical energy without the need of rotary-to-linear converter. As a kind of linear actuators, the Linear Swithced Reluctance Actuator (LSRA) has achieved a great development due to its benefits on simple structure, low manufacturing cost and no rare-earth permanent magnets that are widely used in high-speed and high-force linear motion mechanism [1, 2, 3]. Furthermore, LSRA has great value and applications, for example machining tools [4], active suspension systems [5], propulsion railway transportation systems [6] and so on. Thus, the demand for linear actuators has registered a continuous growth in recent years. Despite of various advantages, LSRA has some drawbacks such as high force ripple, vibration and low force density compare to linear permanent magnet actuator (LPMA) [7, 8, 9, 10]. In order to increase the diversity of the LSRA applications, it is important to find a way to design the LSRA effectively and improve the actuator performances.

The structure of the LSRA can be categorized into three which are planar single-sided, planar double sided and tubular topology. For example, Lee *et al.* [11] proposed a standard design procedure for a single-sided and longitudinal flux based linear switched reluctance machine that consist of six mover poles and nine stator poles. Meanwhile, Lobo *et al.* [12] compared four possible structure of LSRA for the vertical propulsion application which were single-sided LSRA, double-sided LSRA, double-sided LSRA with an inner stator, and double-sided LSRA with modified mover. The generated thrust force of conventional single-sided LSRA is relatively low due to the reason of lower magnetic flux density compare to other designs. Pan *et al*. [13] presented a LSRA with double-sided asymmetric structure. This motor structure ensures the alleviation of motor saturation magnetization effect, higher thrust force density and acceleration. However, the LSRA with tubular topology seems to be attractive for industrial purposes due to both its closed form and the inherently absence of attractive force between stator and mover. Besides that, tubular LSRA also has some important advantages in comparison to the single-sided LSRA such as low flux leakages and larger force density, even than double-sided LSRA [14]. Therefore, researchers began to explore the LSRA design with tubular topology.

A novel three phases transverse flux tubular switched reluctance motor with active stator and passive mover is proposed by Viotel *et al*. [14]. The designed motor has performed an impressive thrust force to volume ratio due to its tubular structure and shorter flux lines path. Llibre *et al*. [15] designed a tubular linear switched reluctance motor function as a left ventricular assist device (LVAD). The proposed motor has lower eddy current losses and normal forces were neutralized due to its tubular structure as compare to the planar type LSRA which lead to higher generated thrust force. Commins *et al.* [16] developed a tubular linear synchronous reluctance motor with thin split laminations on mover part. The complex structure developed for the teeth and laminations provide a better generated thrust force and consistent flux density throughout the flux part. Meanwhile, Yan *et al*. [17] and Li *et al*. [18] proposed a novel design of four phases 8-6 tubular switched reluctance motor with double excitation windings to overcome the problem of low force production of LSRA. The two sets of windings applied on the stator and mover help to improve the generated thrust force and the motor efficiency as the linear motor utilized the design space on both stator and mover. Nonetheless, the research on the tubular LSRA still new compare to planar LSRA and yet the design of tubular LSRA is still valuable to investigate.

The objective of this paper is to propose a tubular linear switched reluctance actuator (LSRA) which consists of 12:8 stator-to-mover pole pairs. The 12:8 stator-to-mover pole pairs tubular LSRA benefits the force improvement of linear electromagnetic machine. The rest

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if this paper is organized as follows. The concept design and operation principle of the tubular LSRA is explained in Section 2. In Section 3, FEM analysis results of the actuator parameters which affect the overall performance of the actuator are analyzed. Finally, the conclusion of this paper is drawn in Section 4.

2. MATERIALS AND METHOD

2.1 LSRA conceptual designs

The schematic structure of the proposed tubular LSRA with 12:8 stator-to-mover pole pairs is shown in Figure-1. The presented tubular LSRA is a three phases actuator with longitudinal configuration which consists of twelve stators and a mover that made up of medium carbon steel (AISI 1045) due to lower material cost compare to low carbon steel and silicon steel which are commonly used. The coil windings are embedded on each of the stator slot and eight coils are connected in series for each phase. In other words, there are 24 coil windings on twelve stators slots to form a three phase actuator due to the minimum number of phases for a tubular LSRA to produce a continuous motion is three. Generally, a three phase actuator usually has the combination of stator and mover pole pairs such as 6:4, 12:8, 18: 12 and so on. Even though the increment of pole pairs cause the poles width and physical size of the coils reduced, the introduction of 12:8 stator-to-mover pole pairs can reduce the noise and vibration in the system compare to 6:4 stator-to-mover pole pairs [19, 20]. The advantages of these actuator with higher pole pairs number on vibration reduction become an important factor in design a precise motion actuator. Hence, a 12:8 stator-to-mover pole pairs ratio tubular LSRA is design and the performance is compare with 6:4 stator-to-mover pole pairs ratio tubular LSRA in term of generated thrust force.

2.2 LSRA driving principle

The operation of tubular LSRA is based on the principle of minimum reluctance. The thrust force and motion of the actuator is generated due to the tendency of the mover to reach a position where the inductance is maximum while the reluctance is at the minimum. The actuator is in the state of maximum reluctance when the active pole pairs between the stators and mover is fully unaligned. Likewise, the actuator is in the state of minimum reluctance when the active pole pairs between stator and mover are fully aligned. Figure-2 shows the magnetic circuit BB', one of the three magnetic circuits. As shown in the figure, when the excitation current is applied to Phase BB' coils, magnetic flux is generated from the coils that is connected in series. The flux flows from the stator poles with the active phase coils straight to the mover poles at the center and back to stator poles to perform a complete magnetic circuit cycle. In order to reduce the reluctance between the stator and mover poles, the mover poles that near to the active phase coils are tends to move toward the stator poles on the right (x-direction) to reach the fully aligned position. As the mover poles are brought to the aligned position with stator poles, the active phase coils are switched. The thrust force is generated when the stator and mover poles are not aligned. By switching the active phase coils with respect to different mover position, the mover will drive in forward or reverse direction continuously according to the sequence of the active phase coils. Applying the excitation current in sequence of phase BB'-AA'-CC' tends to drive the mover towards forward direction continuously. Meanwhile, applying excitation in sequence of CC'-AA'-BB' causes the reverse motion of the mover. The sequences for forward and reverse directions in the first pitch for the designed tubular LSRA with a single pitch length of 15mm are shown in Table-1 and Table-2.

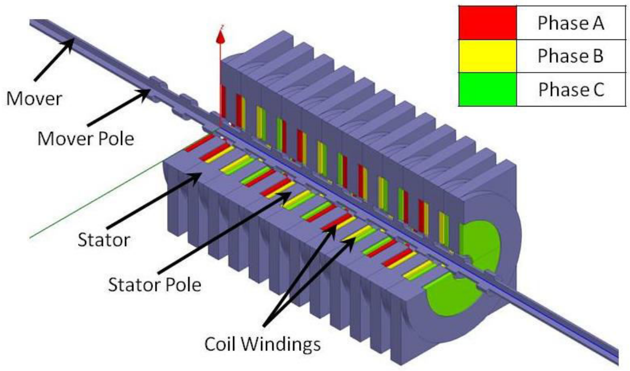

Figure-1. Schematic structure of the proposed tubular LSRA.

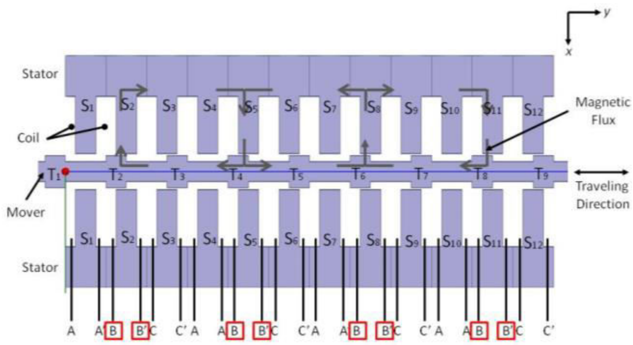

Figure-2. Magnetic circuit of the proposed tubular LSRA for Phase B.

Table-1. Forward motion sequence in the first pitch.

Position (mm)	Phase	Stator	Mover
0-2.5	BB'	S_2- S_5- S_8- S_{11}	T_2- T_4- T_6- T_8
2.5-7.5	AA'	S_1- S_4- S_7- S_{10}	T_1- T_3- T_5- T_7
7.5-12.5	CC'	S_3- S_6- S_9- S_{12}	T_3- T_5- T_7- T_9
12.5-15	BB'	S_2- S_5- S_8- S_{11}	T_2- T_4- T_6- T_8

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Table-2. Reverse motion sequence in the first pitch.

Position (mm)	Phase	Stator	Mover
0-2.5	CC'	S_2- S_5- S_8- S_{11}	T_3- T_5- T_7- T_9
2.5-7.5	AA'	S_1- S_4- S_7- S_{10}	T_1- T_3- T_5- T_7
7.5-12.5	BB'	S_3- S_6- S_9- S_{12}	T_2- T_4- T_6- T_8
12.5-15	CC'	S_2- S_5- S_8- S_{11}	T_3- T_5- T_7- T_9

2.3 Structure parameters optimization

The structure parameters of tubular LSRA has significant influence on the performance of the designed actuator. The proposed tubular LSRA undergo the optimization on the mover pole height and pole width for both stator and mover in order to maximize the performance of the designed actuator. The tubular LSRA structure design presented in this paper is shown in Figure-3 and the major parameters for the tubular LSRA are shown in Table-3.

3. RESULTS AND DISCUSSIONS

In this section, the results of the simulation for tubular LSRA are presented. The results focuses on optimizing the tubular LSRA design, by varing three (3) parameters; i.e. (a) number of stator-to-mover pole pairs,

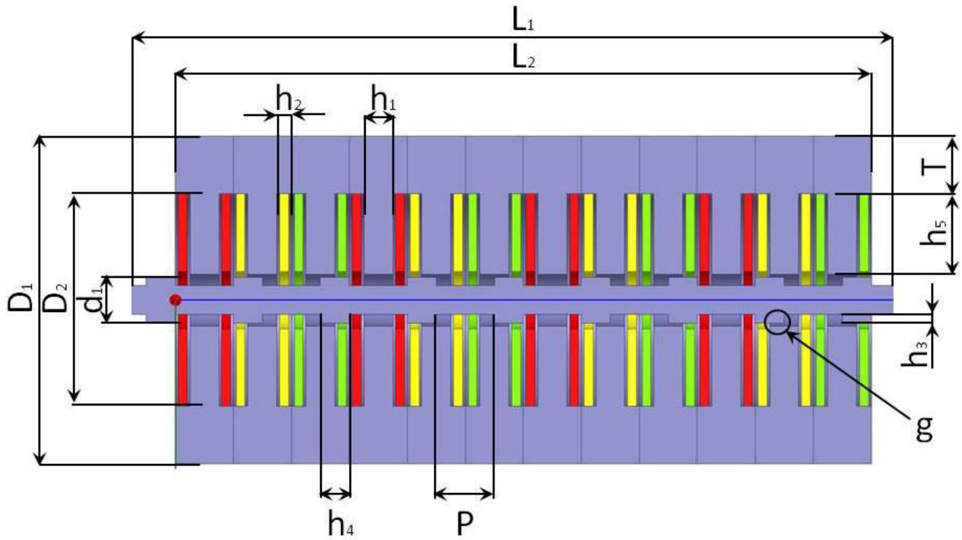

Figure-3. Major structure parameters of the proposed tubular LSRA.

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Table-3. Parameters of the tubular LSRA.

Parameter	Symbol	Value
Stator-to-mover pole pairs ratio	$R_{S:M}$	12:8
Actuator materials	M_t	AISI 1045
Number of winding turns	n	60
Number of phases	P_h	3
Number of coil per phase	N	8
Stator outer diameter	D_1	57 mm
Stator inner diameter	D_2	37mm
Stator yoke thickness	T	10 mm
Stator tooth width	h_1	5 mm
Stator slot width	h_2	2.5 mm
Stator tooth height	h_5	14 mm
Stator length	L_2	120 mm
Mover outer diameter	d_1	8 mm
Mover tooth height	h_3	1.5 mm
Mover tooth width	h_4	5 mm
Mover tooth pitch	P	10 mm
Mover length	L_1	420 mm
Air gap thickness	g	0.5 mm
Coil diameter	D_c	0.5 mm

(b) mover tooth height, and (c) tooth width. A computational study was conducted by using commercial 3D Finite Element Method analysis (FEM) analysis software (Maxwell 3D Version 17.0) in order to evaluate the thrust force generated by the tubular LSRA.

3.1 Number of stator-to-mover pole pairs, $R_{S:M}$

Pole pairs number is an important factor that will affect the output performance of a linear electromagnetic actuator. In general, the stator-to-mover pole pairs of a three phases linear electromagnetic actuator usually used the combination of 6:4, 12:8, 18:12 and so on. The numerical computation is conducted on the output thrust force of the proposed tubular LSRA between 6:4 and 12:8 stator-to-mover pole pairs but the overall system dimensions are held constant as in Table-3. Figure-4 shows that the generated thrust force for 12:8 stator-to-mover pole pairs is larger compare to 6:4 stator-to-mover pole pairs under the same winding turns. When the excitation current is at 2 A, the generated thrust force for 6:4 stator-to-mover pole pairs tubular LSRA reaches 0.27 N. Meanwhile, the generated thrust force of tubular LSRA with 12:8 stator-to-mover pole pairs ratio is 0.89 N which is approximately three times larger generated thrust force compare to the previous design. Although both of the design are three phases linear machine, 12:8 stator-to-mover pole pairs has four working pole pairs per phase and 6:4 stator-to-mover pole pairs has two. In addition, 12:8 stator-to-mover pole pairs offer a shorter magnetic flux path and lesser energy losses which resulting the generated thrust force is probably larger than the latter design at the same output power.

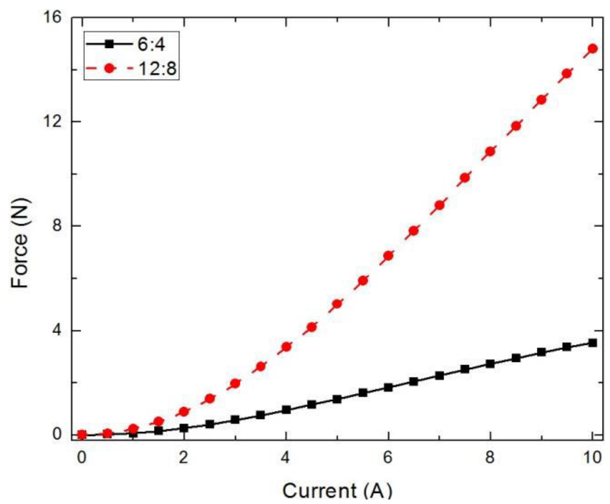

Figure-4. Output performance of different stator-to-mover pole pairs number.

3.2 Influence of mover tooth height, h_3

In this part of analysis, the variables are mover tooth height and excitation current. The geometrical parameters are kept constant as shown in Table-3. In order to ensure the efficiency of the actuator at maximum

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generated thrust, the mover tooth height is varied and optimized from 1 mm to 3 mm with interval of 0.5 mm. The influence of the mover tooth height on the generated thrust force for the designed tubular LSRA is shown in Figure-5. As indicated in Figure-5, the generated thrust force for the actuator is highest which reaches 5.4 N at excitation current of 5 A when the mover tooth height of 1.5 mm. However, force saturation happened when the mover tooth height is larger than 2 mm where further increasing of the tooth height draw to the decreasing of generated thrust. Additionally, the generated thrust is directly affected by the magnetic flux of the actuator when the mover tooth height is changed. Figure-6 shows that increase the mover tooth height cause the magnetic flux to become smaller. Hence, this proves that by increasing the mover tooth height will cause the magnetic flux and generated thrust force to become smaller.

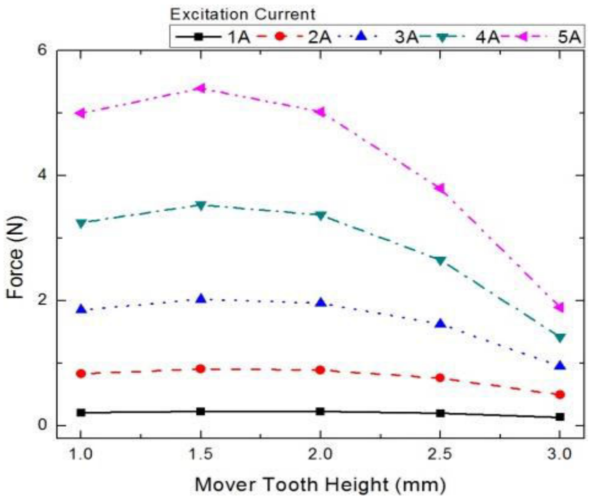

Figure-5. Influence of mover tooth height on generated thrust force.

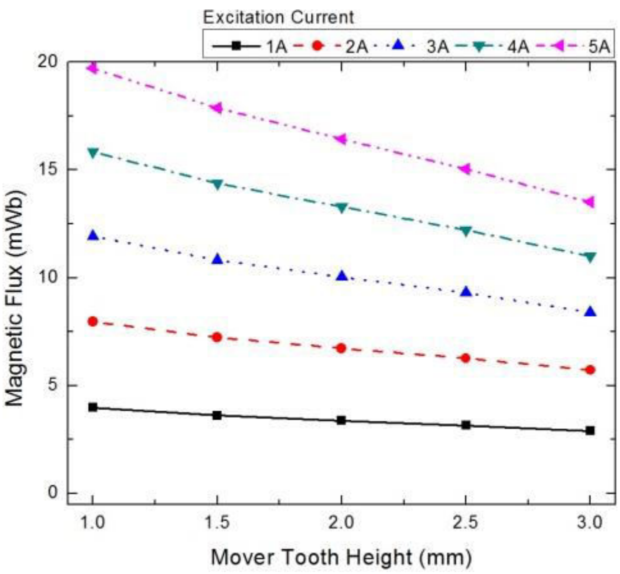

Figure-6. Influence of mover tooth height on magnetic flux profile.

3.3 Influence of tooth width, h_1 / h_4

The variables in this part of analysis are stator and mover tooth width with different excitation current. The adjustment of the stator and mover tooth width appears as an alternative for increasing the machine efficiency, since the overlapping area between stator and mover tooth width is directly affected towards the generated thrust force. However, the adjustment of the tooth width between stator and mover will be varied in parallel which mean the stator and mover tooth width has the same value. Firstly, the purpose of designing the linear actuator with similar tooth width is to prevent the occurrence of dead zone and becomes larger as the absolute difference between stator and mover tooth width increases. Additionally, this zone also does not contribute to the generation of thrust force for the tubular LSRA. Next, similar tooth width also can reduce the actuator from generating a larger vibration to the system.

The sensitivity of the tooth width on the tubular LSRA is examine by varying the tooth width between 3 mm to 8 mm. The generated thrust force and magnetic flux profiles respectively for specific tooth width is shown in Figure-7 and Figure-8. As indicated in Figure-7, the generated thrust force is increasing when the tooth width increase from 3 mm until 5 mm and reaches the highest with force value of 5.4 N at 5 A excitation current when it is 5 mm. However, when the tooth width increase and larger than 5 mm, the actuator start to undergo thrust force saturation, as further increase of tooth width cause the generated thrust force to be reduced even though the magnetic flux in the actuator increase when larger tooth width applied. Hence, the optimum tooth width for the tubular LSRA is 5 mm which the generated thrust force is the highest.

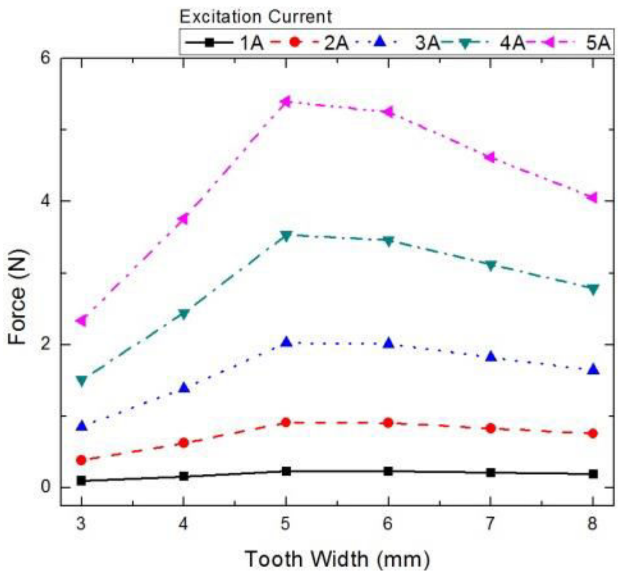

Figure-7. Influence of tooth width on generated thrust force.

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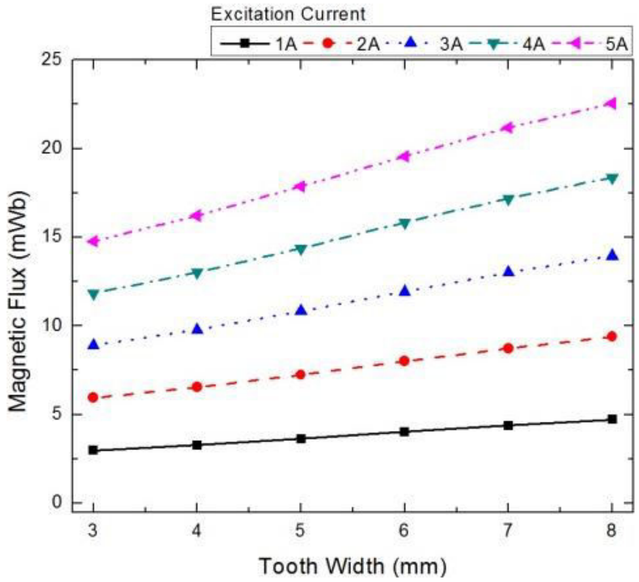

Figure-8. Influence of tooth width on magnetic flux profile.

3.4 Static force characteristic of tubular LSRA

The relationship between the output thrust force generated and mover position with different excitation current is presents in Figure-9. The output thrust force is the static thrust force generated by single phase excitation of the designed machine. When 0.5 A excitation current is apply, the thrust force generated by the machine is only ± 0.59 N. However, the thrust force increase as the excitation current increase and it reaches ±2.05 N when 3 A excitation current is apply. Next, Figure-10 shows the electromagnetic force of the machine when all phases windings are working. It can be found that the output thrust force is approximately a sine curve, and the thrust force value is fluctuates between 0.40 N and 0.93 N when all phases winding working under 2 A excitation current. However, a higher excitation current can significantly increase the generated thrust force but depend on the applications and force require.

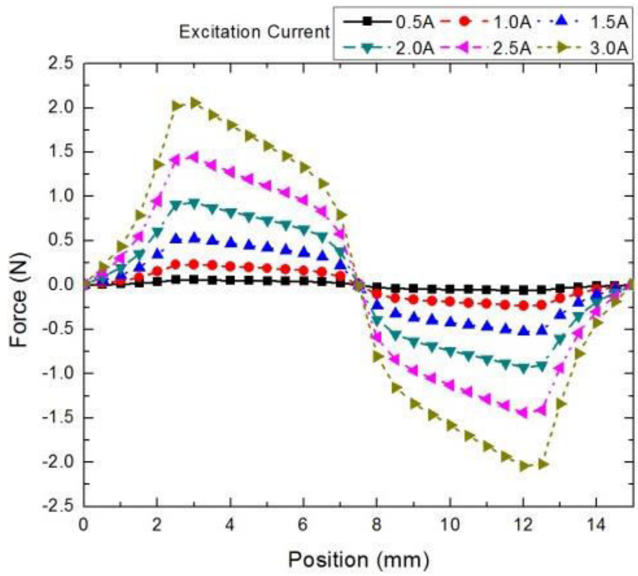

Figure-9. The electromagnetic force generated by one phase of tubular LSRA.

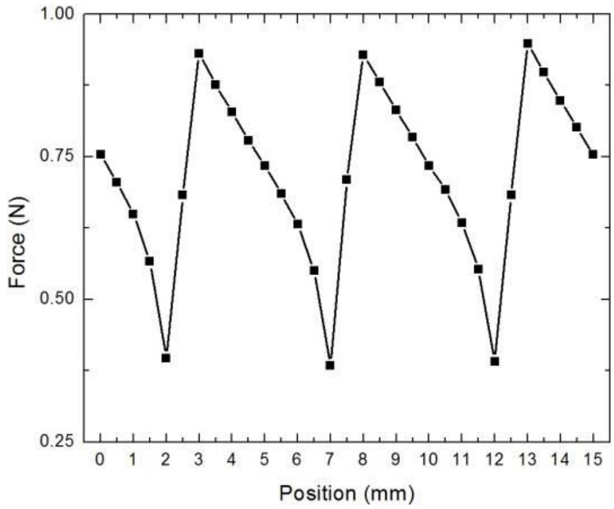

Figure-10. The electromagnetic force of tubular LSRA when all phases windings are working at 2A.

4. CONCLUSIONS

In this paper, a tubular linear switched reluctance actuator (LSRA) without permanent magnet that has 12:8 stator-to-mover pole pairs was proposed. The relations between the tubular LSRA parameters were investigated in order for optimum the performance of the designed actuator. The comparison between the tubular LSRA with 6:4 and 12:8 stator-to-mover pole pairs is conducted and the result shows that 12:8 stator-to-mover pole pairs able to generate a higher thrust force compare to 6:4 stator-to-mover pole pairs. The actuator parameters such as mover tooth height and tooth width are the two major parameters that usually will influence generated thrust force when designing the actuator which the parameters need to be optimized in order to obtain the optimum actuator performance. From the simulation results, the proposed actuator with optimized design parameters generates the maximum output thrust force for approximately 2.05 N

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with the applied excitation current of 3 A. In order to further improve the performances of tubular LSRA, the influences between more actuator parameters should be optimized depending on the applications. Therefore, the proposed tubular LSRA is more attractive and can be subject of future study.

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