Influence of Materials, Air Gap and Winding Turns for a Tubular Linear Switched Reluctance Actuator (TLSRA)

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Abstract— **This paper presents the design and optimization of Tubular Linear Switched Reluctance Actuator (TLSRA). The study is carried out by means of Finite Element Method (FEM) by using ANSYS Maxwell software which capable of predicting the TLSRA thrust force. The study covered the variation of three parameters which are actuator materials, actuator air gap thickness and number of winding turns. In this design, the medium carbon steel (AISI 1045) is used for the actuator materials due to lower materials cost and higher thrust force generated compare to low carbon steel (AISI 1008 & AISI 1010) at current applied more than 1.8 A. In order to overcome the issue of TLSRA on low force density, the optimization of actuator air gap thickness and number of winding turns are important parameters that will influence the inductance and magnetic flux of TLSRA. The results show that the actuator produced larger thrust force with the air gap thickness of 0.5 mm and number of winding turns of 300 turns where it reaches 10.16 N when 3.6 A current is applied.**

Index Terms— **Air Gap; Carbon Steel; Switched Reluctance Actuator; Thrust Force; Winding Turns.**

I. INTRODUCTION

The development of linear actuators is today a research field of interest to the field of engineering and technology. Linear actuator mechanisms such as LSRA have increasingly been being considered as the actuator can decrease the reliance on rotary to linear motion converters [1]. In recent years, Linear Switched Reluctance Actuators (LSRA) have attracted the attention of researchers due to the advancement in the power electronics technology, digital signal processing, and control strategy. LSRA regardless the issues on high force ripples and acoustic noise are being focused of increasing interest and demand due to several advantages over other types of the linear actuator such as lack of mechanical gears, simple in structure, the absence of permanent magnet and low manufacturing cost [2]-[3].

In general, the structure of LSRA consists of three major parts which are stator, mover, and windings. As for a linear type of switched reluctance actuator, the windings can be set at either stator or mover. The thrust force and motion of the actuator are generated due to the tendency of the mover to reach a position where the inductance of the actuator is maximized, and the reluctance is minimum [4]. Nevertheless, the LSRA will be generated lower thrust force compare to the hybrid type of LSRA which contain rare earth material or permanent magnet for approximately 60% [5].

The structure of TLSRA seems to be attractive for industrial purpose due to both closed form and the inherent absence of attractive force between the stator and mover. Even though there are many research done on force ripples and acoustic noise minimization, low force density is another weakness of TLSRA need to overcome. In order to increase the diversity of applications, it is important to improve the force density of TLSRA. Some of the strategies used to achieve the force density improvement are optimization of TLSRA parameters, modification of pole or teeth shape on stator or mover and laminated steel design. The design of tubular linear electromagnetic actuator with Finite Element Analysis Method (FEM) was discussed to obtain the optimum air gap thickness, a number of winding turns and actuator size [6]. The comparison between the force performance of longitudinal flux configuration and transverse flux configuration shows that TLSRA with longitudinal flux configuration generated a larger attraction force and required a lesser amount of steel in the mover part compared to the transverse flux configuration [7].

On the other hand, TLSRA with skewed poles was proposed to reduce the force ripple and improve the force density as compared with the conventional design [8]. In addition, the proposed design improves the starting force of TLSRA due to a reduction in mass and volume. Besides that, pole shoes affixed to the side of stator poles were introduced to minimize force ripple and volume of TLSRA while the force density is improved [9]. Then, the laminated silicon steel was used on the actuator design for improving magnetic flux and force density [10]. Furthermore, the added volume density helps to diminish the eddy current occurred in the TLSRA. Meanwhile, eddy current loss and motor core loss in the switched reluctance actuator can be reduced by applying a thin layer of lamination steel on the motor which allows larger magnetic field strength [11].

With the purpose of optimizing the design and maximizing the performance of TLSRA, this paper covered three variations of parameters which are types of steel, air gap thickness, and a number of winding turns. The simulation focuses on the influence of variation of some constructive parameters of the TLSRA on the thrust force generation involves the application of finite-element method (FEM) base simulation analysis.

II. METHODOLOGY

The TLSRA concept design presented in this paper is shown in Figure 1 and Figure 2. Its major TLSRA parameters are shown in Table 1. The presented TLSRA consists of an active mover and passive stator. Each stator slot will contain a coil of copper winding. A three phase TLSRA will have two coils per phase which the coil is connected in series connection, but the winding direction is in the opposite direction to ensure the flow of magnetic flux in maximum. Then, the presented TLSRA has a longitudinal configuration. The simulation was carried out based on the type of steel, number of winding turns per phase and air gap thickness between stator and mover by using ANSYS Maxwell.

Table 1
Parameters of the Designed TLSRA

Parameters	Symbol	Value (mm)
number of winding turns	n	300
number of phases	P_h	3
number of coil per phase	N	2
stator outer diameter	D_1	63
stator inner diameter	D_2	20
stator tooth width	h_1	4
stator slot width	h_2	12
stator length	L_1	100
move outer diameter	d_2	15
mover tooth height	h_3	4.5
mover tooth width	h_4	4
mover tooth pitch	P	11
mover length	L_2	320
air gap thickness	g	0.5
coil diameter	D_c	0.5

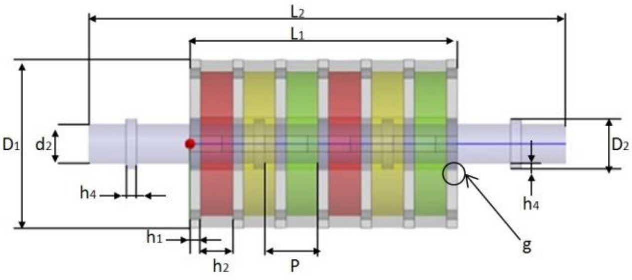

Figure 1: Design of TLSRA top view

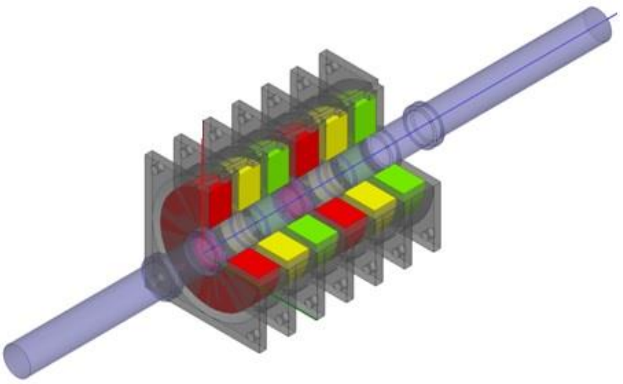

Figure 2: Design of TLSRA 3D view

III. RESULTS AND DISCUSSION

In this section, the results of the simulation for the TLSRA are presented. The results of variation three actuator parameters are obtained: type of steel, air gap thickness and number of winding turns. Thrust force generated by the actuator is used as the reference to determine the optimized parameter in order to maximize the thrust force of TLSRA.

A. *Type of Materials*

Silicon steel is widely used as the material to design the electromagnetic actuator. Other than that, low carbon steel is an alternative material of silicon steel due to lower material cost compared to silicon steel. However, the material cost for medium carbon steel is much cheaper compare to both silicon and low carbon steel. Hence, the investigation and comparison of TLSRA performance is conducted with low carbon steel and medium carbon steel. The difference between three types of steel is the amount of carbon content that contains in the steel where increasing the amount of carbon will reduce the conductivity of the materials. The element of three types of carbon steel is shown in Table 2.

Table 2
Materials Properties

Element	Low Carbon Steel		Medium Carbon Steel
	AISI 1008	AISI 1010	AISI 1045
iron, Fe	99.31-99.70	99.18-99.62	98.51-98.98
manganese, Mn	0.30-0.50	0.30-0.60	0.60-0.90
carbon, C	0.08-0.10	0.08-0.13	0.42-0.50
sulphur, S	0.050	0.050	0.050
phosphorus, P	0.040	0.040	0.040
electrical conductivity, G (room temperature)	6.85M S/m	6.99M S/m	5.63M S/m

Figure 3 shows the thrust force against input current for three different types of carbon steel. As indicated in Figure 3, low carbon steel has larger thrust force compare to medium carbon steel as the current excitation current increases from zero to 1.6A. The thrust force reaches 6.08N for AISI 1008 and 5.96N for AISI 1010 while AISI 1045 has the smallest thrust force with 5.71N at 1.6A. This is due to the low carbon steel able to generate stronger magnetic field as the carbon content in this type of steel lesser compare to medium carbon steel. Hence, low carbon steel has better electromagnetic properties and electrical conductivity properties. As the excitation current reach 1.8A an above, AISI 1045 starting to have larger thrust force generated compare to both AISI 1008 and AISI 1010. At 3.6A, the thrust force reaches 7.99N for AISI 1008 and 7.75N for AISI 1010. However, TLSRA with material AISI 1045 generated higher thrust force compare to low carbon steel which reaches 10.16N. At this point, low carbon steel generated lower thrust force value compares to medium carbon steel due to medium carbon steel reaches the saturation point where the increasing in excitation current does not has much influence on the thrust force generated. So, medium carbon steel can be an alternative material as it is cheaper and the saturation point for AISI 1045 is larger than low carbon steel.

B. *Variation of Air Gap Thickness*

In order to increase the efficiency of the designed actuator, the reduction of the air gap thickness is a good alternative for increasing the thrust force. In this design, the air gap thickness is varied from 0.5 mm to 1.5 mm with the interval of 0.2 mm. The results of the thrust force generated for different air gap thickness for TLSRA is shown in Figure 4. The graph shows the thrust force in response to the applied excitation current from zero to 3.6 A. As indicated in Figure 4, the increasing of the air gap thickness will cause the actuator thrust force to be reduced. For the smallest air gap thickness, which the size of the air gap is 0.5 mm, the thrust force reaches 10.16 N when the 3.6 A of current is applied. However, as the air gap increase to 1.5 mm, the thrust force generated by the TLSRA reaches only 2.74 N when the 3.6 A of current is applied. Figure 5 shows the influence of varying air gap thickness when current 3.6 A is applied. The increase in the air gap thickness leads to the reduction of thrust force generated due to larger air gap will increase the reluctance of the TLSRA. Hence, the reluctance will results reduction in magnetic flux, inductance, and thrust.

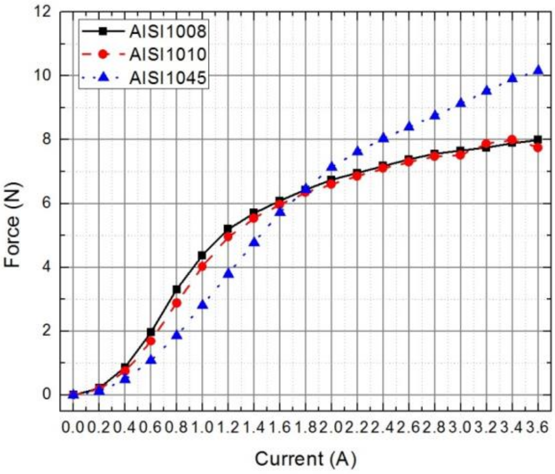

Figure 3: Comparison between performances of TLSRA with different types of steel

C. Variation of Winding Turns

There are two factors that will influence the magnetic flux, inductance and thrust force of the actuator which is number of winding turns and excitation current. As the number of winding turns for the coil increase, it will increase the inductance of the actuator. However, it is important to note that, the increase in the number of winding turns leads to the increase of stator slot area where a larger stator slot required which will reduce the force density of TLSRA. Figure 6 and Figure 7 depicted the performance of TLSRA with variation number of winding turns. When the applied current is 3.6 A, the thrust force reaches 0.48 N for 50 turns and highest thrust force produced, 10.16 N for 300 turns. Hence, the results indicate that higher number of turns per phase will increase the thrust force of TLSRA.

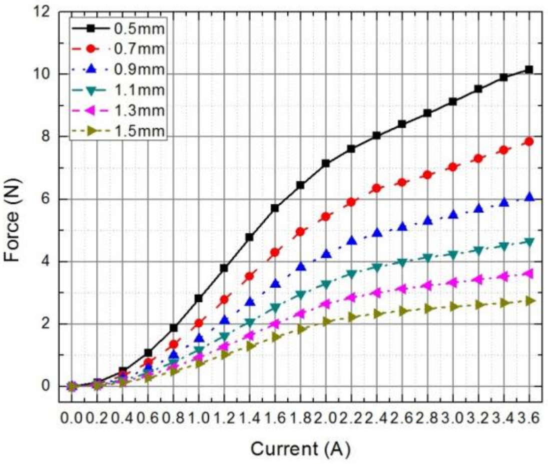

Figure 4: Influence of air gap thickness on thrust force

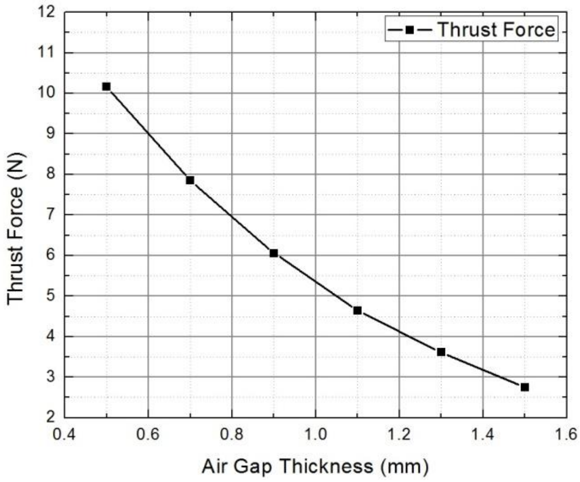

Figure 5: Influence of air gap thickness on thrust force at current of 3.6A

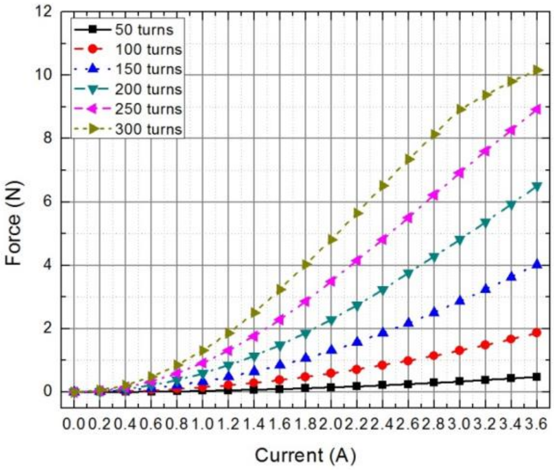

Figure 6: Influence of winding turns on thrust force

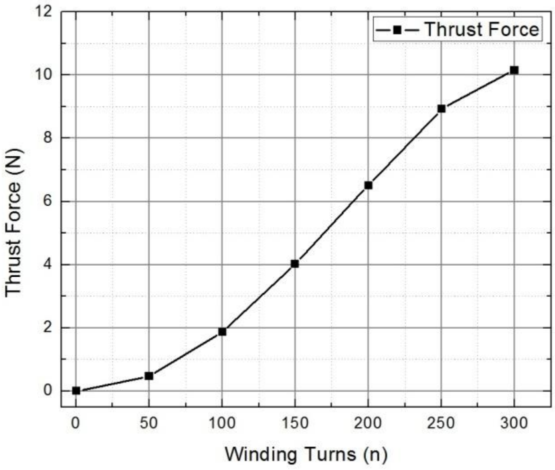

Figure 7: Influence of winding turns on thrust force at a current of 3.6A

IV. CONCLUSION

The paper investigates the performance of TLSRA with three types of carbon steel which are AISI 1008, AISI 1010 and AISI 1045. The results show that low carbon steel (AISI 1008 & AISI 1010) can produce larger thrust force at low current while medium carbon steel (AISI 1045) can perform and generate better thrust force when the high excitation current is applied. Hence, low carbon steel is an alternative material to silicon steel and low carbon steel due to low material cost. Then, the designed studies have shown that the actuator with smaller air gap thickness has the tendency to generate larger thrust force due to the reduction in the reluctance. The air gap thickness with 0.5 mm has highest thrust force (10.16 N when 3.6A) generated compare to other actuator with larger air gap thickness. Other than that, as the number of winding turns increase from 50 turns to 300 turns, the thrust force increases from 0.48 N to 10.16 N when 3.6 A current is applied due to TLSRA produced larger inductance. The TLSRA can be optimized with the analysis of the relation between more parameters in order to improve the issue on low force density depends on the application.

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REFERENCES

[1] V. S. C. Teixeira, D. N. Oliveira, H. Cunha, L. L. N. Reis, and R. S. T. Pontes, “Influence of the Project Parameters on the LSRM - Project Optimization,” in Proceedings of IEEE International Electric Machines and Drives Conference, IEMDC 2007, Antalya, Turkey, 2007, vol. 1, pp. 554–558.

[2] M. Dowlatshahi and M. Daryanush, “A Novel Modified Turn-on Angle Control Scheme for Torque-Ripple Reduction in Switched Reluctance Motor,” International Journal of Power Electronics and Drive Systems, vol. 7, no. 4, pp. 1110–1124, 2016.

[3] M. M. Ghazaly and Sato K., “Basic Characteristics of a Multilayer Thin Electrostatic Actuator Supported by Lubricating Oil for a Fine-motion Stage”, Precision Engineering, vol. 36(1), pp.77-83, 2012.

[4] D. Ravikumar, V. S. Murty, and S. Jain, “Linear Switched Reluctance Motor for High Speed Transit System,” in IEEE Student’s Conference on Electrical, Electronics and Computer Science, Bhopal, India, 2016, pp. 1–4.

[5] J. Garcia, P. Andrada, and B. Blanque, “Assessment of Linear Switched Reluctance Motor’s Design Parameters for Optimal Performance,” Journal of Electric Power Components and Systems, vol. 43, no. 7, pp. 810–819, 2015.

[6] M. M. Ghazaly, A. Y. Tawfik, C. A. Aliza, Z. Abdullah, M. A. Md Ali, and M. A. Nursabillilah, “Force Characteristic of a Tubular Linear Electromagnetic Actuator Using Finite Element Analysis Method (FEM),” Jurnal Teknologi, vol. 78, no. 11, pp. 217–225, 2016.

[7] S. Darabi, A. Mohammadi, and S. H. Hemati, “Advantages of longitudinal flux linear switched reluctance motor compared to transverse flux linear switched reluctance motor for levitation purposes,” in Canadian Conference on Electrical and Computer Engineering (CCECE), 2011, pp. 832–835.

[8] V. Ganesh Sampath, R. Elavarasan, N. C. Lenin, and R. Arumugam, “A Novel Skewed Linear Switched Reluctance Motor – Analysis and Design,” Applied Mechanics and Materials, vol. 787, pp. 874–877, 2015.

[9] N. C. Lenin and R. Arumugam, “A Novel Linear Switched Reluctance Motor: Investigation and Experimental Verification,” Songklanakarin Journal of Science and Technology, vol. 33, no. 1, pp. 69–78, 2011.

[10] M. T. Myo, “Design and Calculation of 75W Three-Phase Linear Switched Reluctance Motor,” World Academy of Science, Engineering and Technology, vol. 48, pp. 108–113, 2008.

[11] J. Kartigeyan and M. Ramaswamy, “Effect of Steel Lamination on Core Losses in Switched Reluctance Motors,” International Journal of Electrical Engineering & Technology (IJEET), vol. 7, no. 6, pp. 64–74, 2016.