Effect of Air Gap in Switched Reluctance Linear Motor Performance

Hasnizah Geno
Politeknik Mersing
hasnizahgeno@pmj.edu.my

Nurul Asyikin Mad Yusof
Politeknik Mersing
asyikin@pmj.edu.my

Azrina Sabiri
Politeknik Merlimau
azrina@pmm.edu.my

Abstract

This paper discusses the effect of air gap on Switched Reluctance Linear Motor (SRLM). Linear motors with permanent magnet are among the best option for applications requiring high acceleration, high speed and high precision. However, permanent magnet usage such as Neodymium Iron Boron (NdFeB) has led to an increment of material cost due to the fluctuating price of rare earth material problems. The alternative solution is by using an electromagnet. To overcome the issue of SRLM on low thrust, the optimization of some important parameters will influence the inductance and magnetic flux. The thrust needs to be maintained for use in high precision applications. The study covered the air gap length, δ parameter which is 0.1mm,0.2mm and 0.3mm. In this design, Solidwork software is used to modeling the SRLM. The static characteristics of the SRLM are calculated using a finite element method analysis (FEM) and the performance of every model has been compared. The SRLM model with optimal performance according to the parameter configurations is when the air gap length is 0.1 mm,3 mm teeth pitch and 0.4 teeth ratio, where the thrust reaches 48 N. In conclusions, the thrust increase when the air gap decrease. Finally, the analysis presents in this paper can be used to determine the best SRLM structure based on the desired thrust with appropriate combination size of the parameter that has been exposed as a guideline to other researchers. It is recommended to study the functionality of the dynamic characteristics of SRLM by developed the motor drive system to enhance the performance of SRLM motor.

Keywords: thrust, air gap, switched reluctance linear motor

1.0 Introduction

In recent years, the SRLM became popular for research and development. The SRLM has been alternative due to a factor of its simple and robust structure where the windings only exist either on the stator or mover part. It can perform well even in severe temperature variations due to the absence of a permanent magnet (Teixeira, Oliviera, Cunha & Pontes, 2006). On top of that, the SRLM inherent easy maintenance, relatively low manufacturing and operational cost (Daldaban & Ustkoyuncu, 2006; Hirayama & Kawabata, 2017). The low manufacturing and operational cost feature of the SRLM are not only due to the simple structure, but also caused by the absence of a permanent magnet inside the structure. The SRLM does not require a mechanical coupling, lead and brush screws, unlike conventional systems that use rotary motors to generate linear movement (Gan, Widdowson, Michael, Tam & Cheung, 2008).

The SRLM is an electromechanical device that develops motion in a single axis, without the use of a mechanism to convert rotary motion to linear motion. Unlike rotary electric motors, the linear motor has a start and an end to its travel. The stator and rotor are unrolled so that instead of producing a torque it produces thrust along its length. Motion is produced as a result of the variable reluctance in the air gap between the mover and the stator. Generally, the SRLM operations are nearly the same with rotational switch reluctance motor. A magnetic field is created in the mover by sending current through the copper coil. When a mover winding is energized, reluctance thrust is produced by the tendency of the mover to move to its minimum reluctance position.

The advanced development of power electronic devices, digital signal processing and control strategies increase the reliability and effectiveness of the switched reluctance type machine, also contributes the SRLM usage wider. The SRLM usually used as the control objects for the high-precision position control applications, high power application, high temperature and high current (Li, Liu & Wang, 2018). The SRLM were used in closed-loop control especially in robotics and biomedical application by using PI controller, hysteresis controller and FDF (Zaafrane, Kediri & Rehaoulia, 2013). The SRLM commonly used in transportation like Light Rail Transit (LRT), lift, pick and place application, conveyor belts, printing and scanning equipment.

However, the SRLM has some drawbacks such produces high thrust ripples and acoustic noise. The thrust ripples production cannot be avoided due to the operating method by AC voltage. It usually causes vibration and acoustic noise during the operation process, hence it reduces the motor integration in high precision position and speed application. The vibration and acoustic noise are usually high in SRLM because of the topology of the structures (Lenin & Arumugam, 2010). The SRLM generate lower thrust compared to the hybrid type of SRLM which contain permanent magnet for approximately 60%. (Garcia, Andrada & Blanque, 2015). To optimize the design and maximize the performance of SRLM, this paper covered the air gap parameter that will influence the magnetic flux of SRLM.

Thus, the aim of this project is to analyze the effect of the air gap to thrust production towards the simulation of SRLM models by displacement of the teeth using finite element method analysis (FEM). Thrust results from each model are compared to obtain the best performance characteristics of SRLM.

2.0 Problem statement

The main component of a linear motor is the permanent magnet. Recently, the motor development facing supply chain problem due to the price of rare earth material fluctuates greatly. The price of neodymium-iron-boron

(NdFeB) permanent magnets (PM) has fluctuated greatly in 2010 and 2011, owing to geopolitical concerns relating to the security of supply (Widmer, Martin & Kimiabeigi, 2015). It's led to an increment of the material cost. The permanent magnet linear motor is expensive due to the use of the permanent magnets used in the motor and the sensing technologies used in the design. The amount of permanent magnet increase with the length of the motor which increases the cost of the linear motor. It became the main constraint for system designers to consider the linear motor design. Whilst the price has become more stable and more reasonable, responsibilities in the environmental sustainability of these materials have further encouraged users to consider alternatives. (Dorrell, Knight, Popescu, Evans & Staton, 2010) conclude whatever the price of rare earth magnets, it is generally recognized that their elimination from electrical machines will lead to a cost reduction.

The cost and difficulty of developing suitable electromagnets had motivated the researcher to study more on SRLM especially on the motor design due on the absence of permanent magnet inside the structure. The different type of magnet material is affected on their respond to magnetic fields thus affecting motor performance. Figure 1 shows the comparisons of the maximum energy product between the magnetic materials.

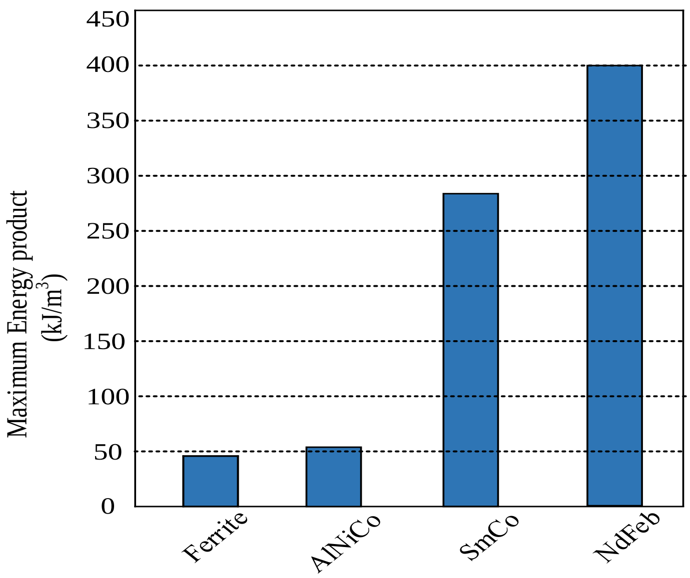


Figure 1: Comparison between the Maximum Energy Product of differing hard magnetic materials (Widmer et al., 2015)

The neodymium-iron-boron magnet has high performance compared to other magnetic material like Aluminium Nickel Cobalt (ALNiCo), Samarium Cobalt (SmCo) and Ferrite. Maximum Energy Product is the measure of the magnetic energy which can be stored, per unit volume, by a magnetic material, it is calculated as the maximum product of a material's residual magnetic flux density or degree of magnetisation and its coercivity (the ability to resist demagnetisation once magnetised). NdFeB magnets generate a very strong magnetic field even in a very small volume but the major drawback is a higher cost. This material is more valuable, so the price of raw materials is doubly more expensive. At the same time, the cost of manufacturing and production of machine prices also increased. Reducing the volume of the high performance NdFeB magnets will reduce the machine cost at the expense of some flux density. Many manufacturer companies shifted from use rare earth permanent magnet. SRLM one of the design without permanent magnet. However, the performance of the motor drop and generated lower thrust for approximately 60% (Garcia, Andrada & Blanque, 2015). Thrust production is influence from the parameter such as air gap, teeth pitch, teeth ratio, material and winding turns (Yeo, Ghazaly, Chong, Jamaludin & Ranom 2018).

3.0 Literature review

In high precision applications, the constant thrust is the most important factor. Several related research was conducted in order to determine the thrust characteristics of the linear motor. Various geometrical parameters also are affecting the features of motor performance, it gives an important influence on the aligned inductance, unaligned inductance, and average force (Wang, Du, Zhang & Wang 2018). A 2-D finite-element analysis was used to investigate the sensitivity of machine geometry on the performance of the SRLM and as guidelines to select the reasonable range of parameters for this machine. The performance of an SRLM was improved by adjusting some dimension detail based on the main structure dimension and parameter from the design procedure. The motor generated a higher thrust by using different pole arcs on the mover and stator. However, other parameters and structure dimensions need to be adjusted further, such as an air gap length and the flux density of the air gap (Zhao,Wang,Yang,& Cheung 2013).

Thus, the air gap length plays one of an important role to ensure the high efficiency of the SRLM. Thrust is sensitive to the air gap length. The increase in the air gap length leads to the reduction of thrust generated due to the larger air gap will increase the reluctance of the SRLM. Hence, the reluctance will result in a reduction in magnetic flux, inductance, and thrust. The gap structure between the mover and stator gives tremendous effects on the output characteristics of the SRLM and this is one aspect of the design requiring a vast review. The maximum thrust can be gained by designing the value of air gap thickness as small as possible. The air gap length must be small to produce low reactance to pass the magnetic circuit and results in effective energy conversion. However, the length must be appropriate to prevent any contact between the stator and mover. If the air gap length is too small, mover cooling is compromised and the mover expands through overheating. It also gives an effect on magnetic field strength, and then reduces the ability to produce thrust. Very small air gap size also gives a side effect on producing error due to the fabrication process is more complicated. If the air gap is too wide, flux density will be reduced and leakage fluxes will increase. Besides that, the permeability of the magnetic also decreases and the magnetizing current will increase. The reduction ability of thrust will occur and drop the SRLM performance. Thus, due to the limitation on manufacturing tolerance, the air gap thickness design is between ranges from 1 mm to 3 mm (Rafajdus, Peniak, Peter, Makys & Szabo. 2014; Faiz & Finch, 1993).

4.0 Methodology

The SRLM is a linear electric motor that has a simple, robust mechanical structure and low cost (Higuchi et.al, 2017). When the motor is driven by the advancement of appropriate controller technology, it is becoming more efficient than the DC or the induction motors. The SRLM structure does not require additional equipment such as wheels and gear because of its linear motion naturally. The SRLM can be designed either in a rectangular or cylindrical shape (Yamamoto & Yamada, 1984). For this research, the rectangular shape of the linear switched reluctance motor is focused.

The basic structure of the proposed SRLM is shown in Figure 2. In this design, the following properties are applied. The structure of the stator and mover is made from ferromagnetic material with grade SS400 stainless steel. The stator and mover have the same size teeth for each model. The stator SRLM is designed with a length size is 96 mm and stator wide is 20 mm. For the SRLM mover, the length size is 48 mm and the mover wide is 30 mm. Stator and mover wide are different due to provide a large area of winding. When the mover area is bigger, many turn of the coil can be filled. The coil embedded inside the mover yoke and the coil is used as an electromagnetic material that creates magnetic flux when the current through it. The stator and mover part is separated by an air gap.

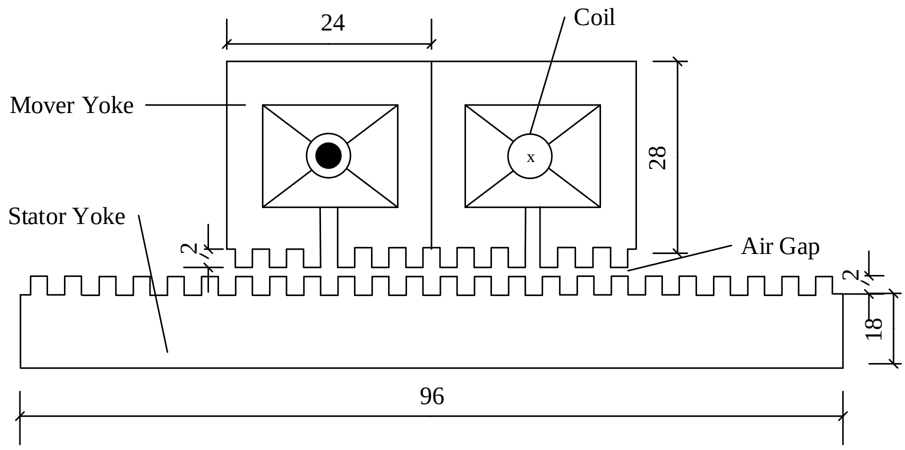
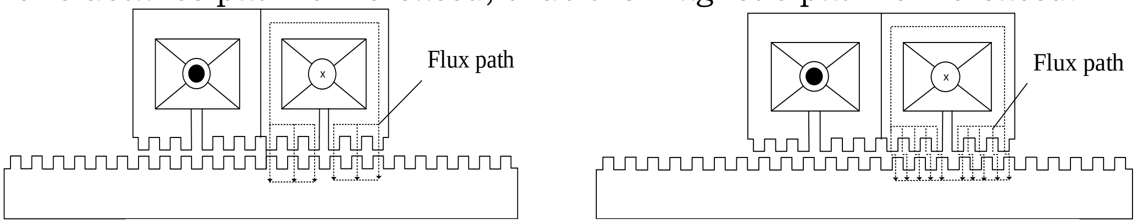


Figure 2: Structure of the SRLM (unit in mm)

The SRLM is a linear electrical machine that converts electrical energy into mechanical energy. The motor operates through the interaction between an induced magnetic field and winding currents to generate thrust. In this research, the SRLM is designed with coil winding without the existence of a permanent magnet. The excitation process occurred when current flow through the coils, induce flux thus generate the magnetic field. Attraction and repulsion between the coil and the steel track create a motion. It travels along a track having a teeth structure. The coils energized attract with the stator and the flux flow in the air gap holds the teeth and the track to be magnetically locked, which is the principal operation of the motor as seen in Figure 3. The flux flow from the mover to the stator, showing that the power is transferred from the mover. Once the coil of the mover is energized, the stator teeth are energized. Therefore, the mover is moving to align with the energized stator teeth. As the mover moves to align with the stator teeth, the reluctance path is decreased. Since the magnetic flux tends to flow through the lowest reluctance path, at this condition the magnetic path is at their peak. On the other hand, when the mover and the stator teeth are in an unaligned position, the reluctance path is increased, thus the magnetic path is increased.



a) Aligned position b) Unaligned position

Figure 3: Flow of magnetic flux

The tendency of the SRLM mover to the point with a minimum reluctance is called reluctance force or thrust. The concept of the thrust is related to the principle of magnetic flux crossing the magnetic circuit. The magnetic flux will flow through the lowest reluctance path; therefore, the mover always tends to align along the minimum reluctance path.

The modelling process of the SRLM is shown in Figure 4. The modelling process of the SRLM structure started with determined the fixed structure of the SRLM. The fixed structure involves the width and length of the stator, mover, and coil. Thus, the basic model of SRLM has the same overall size. By the same overall size, the variation model was developed by applying the variable parameter on a certain structure parameter. The variable parameter has been implemented on the SRLM structure to observe the performance of each model. The model was adjusted in terms of air gap length δ, teeth pitch τ_p.

Once the model of the SRLM has been created, the model was imported and simulated using FEM software. Since the SRLM was designed in rectangle shape, 2D axismetric modeling was used. The material setting of each part has been declared. Declaration of material and other configurations were carried out to ensure the correct simulation process. The simulation parameter involved type of material, motion profile, thrust area and excitation setting for current, coil turn and coil resistance. Table 1 shows the simulation setting for SRLM.

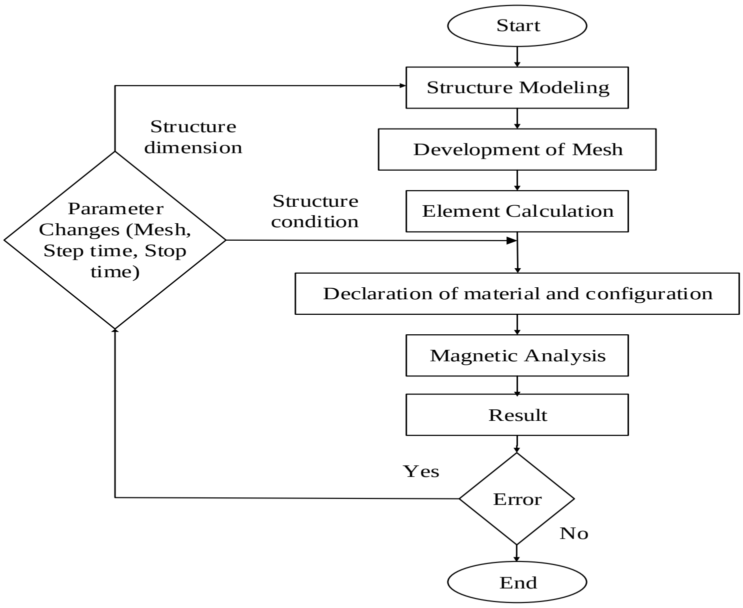


Figure 4: Flowchart for FEM modeling

Table1: Simulation setting for SRLM

No	Parameter	Value
1	Coil turns	330
2	Resistance Coil, R (Ω)	4.63
3	Copper wire diameter, $Ø_c$ (mm)	0.5
4	Current, I (A)	0.1~1

Next is the element calculation process which is only started when the creation mesh of the SRLM is done. The development of mesh on each SRLM model was set based on their structure. The thrust of the SRLM is developing at the air gap region between mover and stator. Therefore, the air gap region between the mover and stator and its near region need to be set finer compared to the other region to get more accurate results. Once the mesh was created, the FEM will start to run the element calculation. The finer element will take a longer time to calculate. Figure 5 shows the mesh created on SRLM designed.

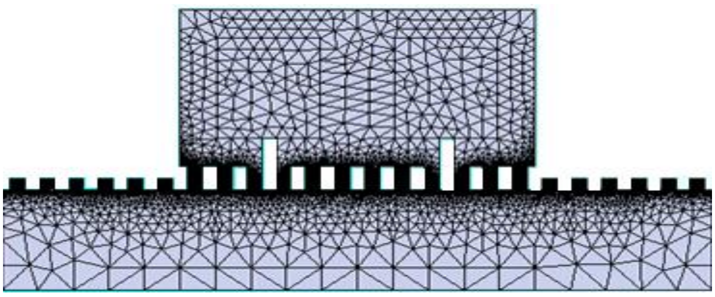


Figure 5: SRLM mesh

Finer meshes relatively produce a higher degree of result accuracy (Liu & Glass, 2013). However, the simulation time will be longer and memory size consumption will be higher. Therefore, the mesh size setting needs to be set appropriately by considering simulation. The right setup, model design structured and various current induced is affected the time allocation required to run the simulation.

The result of the magnetic analysis will be in the form of magnetic flux density and magnetic flux line. Figure 6 and Figure 7 shows a sample of the magnetic analysis result of the SRLM.

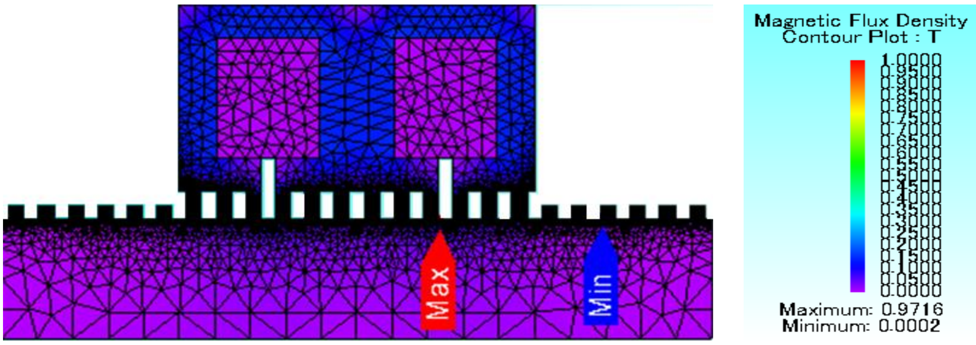


Figure 6: Magnetic flux density of SRLSM

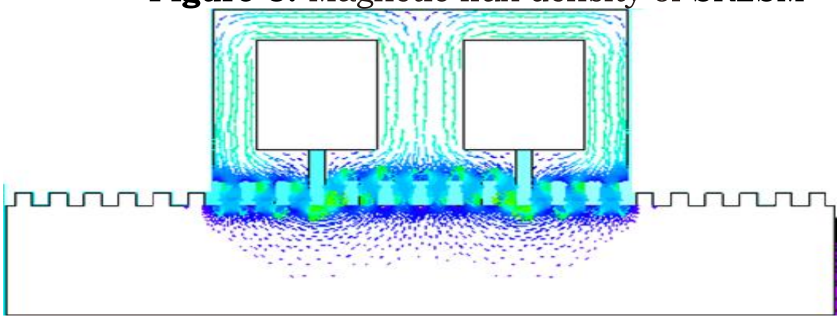


Figure 7: Magnetic flux line of SRLM

The magnetic flux density is related to the production of the SRLM thrust. For this research, the thrust value is obtained directly by FEM and the calculation is based on the resulting flux. Inductance, L is obtained by using the Equation 1 to calculate the resulting flux. Inductance calculation is performed for two main mover positions where are when the mover is fully aligned and when the mover completely unaligned. The two mentioned positions yield to the minimum and maximum inductances, respectively. Lastly, thrust value is gained by applying the inductance value into Equation 2. Thrust is proportional to the rate of change of inductance and is currently being charged on every model.

$$L=\frac{\phi}{I} \tag{1}$$

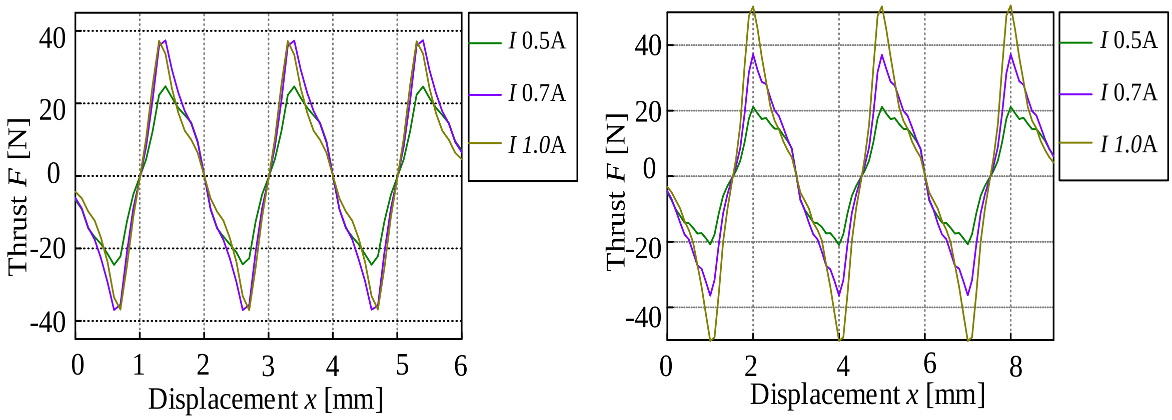
$$F=\frac{1}{2}i^2\frac{dL(i,x)}{dx} \tag{2}$$

5.0 Results and discussion

In SRLM, there are several analyses with varied parameters that had been done. In this project, there are parameters had been varied such as the teeth pitch, the pitch ratio, and the air gap. While the analysis is done for the different air gap length setting. The design was analysed and the effect is determined in terms of thrust and displacement. The graph of thrust versus displacement is obtained. The mover will move until it reaches the peak value of thrust and dropped slowly as the value of thrust decreasing. Generally, increasing current will increase the value of thrust. The thrust of the SRLM is proportional to the current *I*. However, the air gap length setting will affect the maximum thrust produce to ensure the thrust increase without exceeding the saturation level.

5.1 Simulation result for 0.1mm air gap length, δ

Figure 8(a) and 8(b) show the results of 0.1mm air gap length. The analysis is carried out in the model for the teeth pitch size=2mm and teeth ratio=0.4. The simulation result of the single phase SRLM showed the thrust at the different instants of time such as represented in Figure 8(a). No magnetic saturation occurred for the model with the value of excitation current between 0.1A to 1A. By making the mover displacement as a reference, x=1.3 mm as a reference, it shows that the thrust produced is F=23 N for current I=0.5A, F=38.3N and F=38.2N for the current injected I= 0.7A and I=0.1A. The maximum thrust obtained is seemed the same between the current injected at 0.7A and 1.0A. It shows that the thrust tends to saturate when the current exceeds 1.0A.



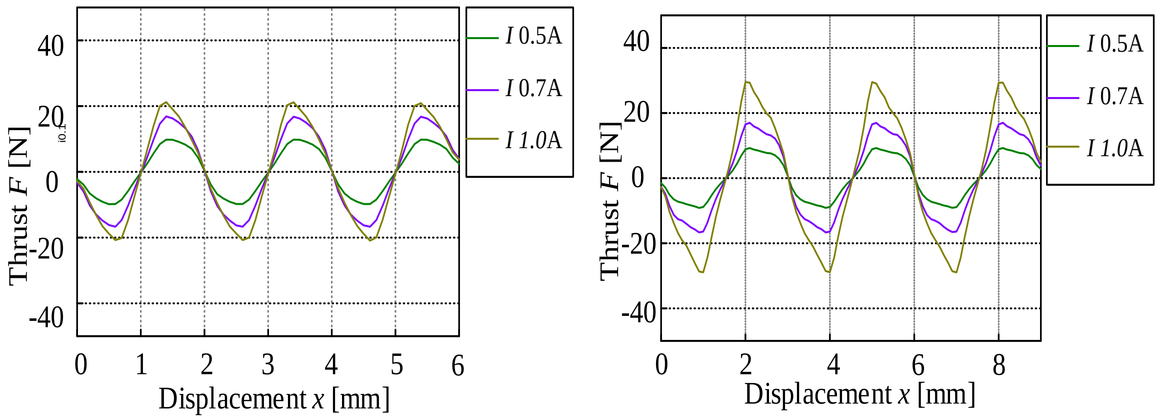
(a) δ=0.1mm, τ_p=2 mm, w_t/τ_p=0.4 b) δ=0.1mm, τ_p=3mm, w_t/τ_p=0.4

Figure 8: Result 0.1mm air gap length

The next model has the teeth pitch=3mm with the teeth ratio is 0.4. Based on the Figure 8(b) the maximum thrust is F=48N when injected current I=1.0A, F=38N when injected current I=0.7A and F=20N during I=0.5A. In this model the thrust is lower than previous design when current I=0.5A and I=0.7A was injected. But the thrust still can increase though the injected current at I=1A. It indicates that the thrust has a potential to continuously increased when the teeth pitch length is bigger.

5.2 Simulation result for 0.2mm air gap length, δ

Figure 9 shows the results of 0.2mm air gap length. In order to identify the effect of air gap in SRLM, the next design model is by using air gap length 0.2mm, teeth pitch size 2mm and teeth ratio is 0.4. Figure 9(a) shows the maximum thrust produces is 15N,18Nand 22N when current injected I=0.5 A, 0.7A and 1A respectively. The thrust increase nicely. While when the teeth pitch is 3mm and teeth ratio is 0.4 the maximum thrust produced is 14 N, 17.6N and 28N as shown in Figure 9(b). Both design model has possibility to produce higher maximum thrust by injected current higher than 1A.

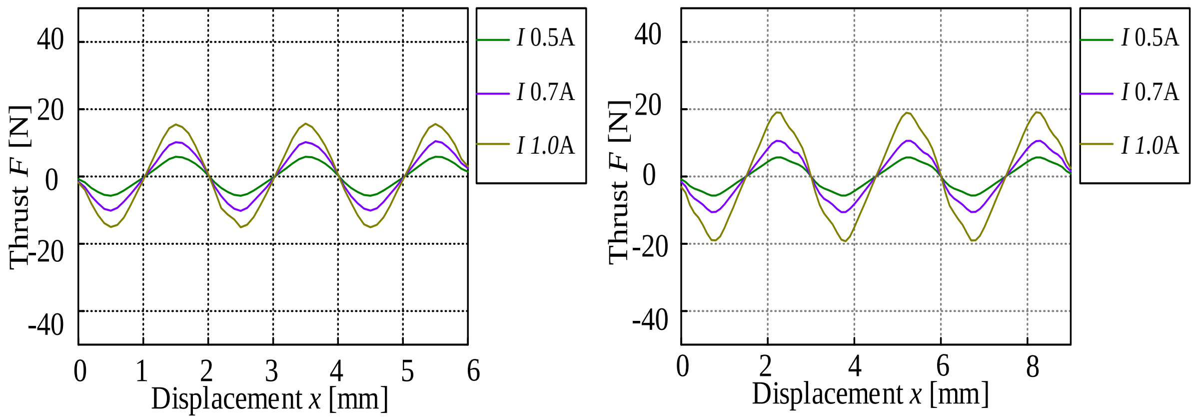


(a) δ=0.2mm, τ_p=2 mm, ω_t/τ_p=0.4 (b) δ=0.2mm , τ_p=3mm, ω_t/τ_p=0.4

Figure 9: Result 0.2mm air gap length

5.3 Simulation result for 0.3mm air gap length, δ

Next, increasing of air gap length, δ to 0.3mm causes the overall maximum thrust is decrease. As shown in Figure 10 (a) current 0.5A, 0.7A and 1A was injected and the maximum thrust produce is 4N, 10N and 16N for teeth pitch 2mm and teeth ratio 0.4. While Figure 10(b) shows the maximum thrust is 4N,10N and 19N for the design model has teeth pitch 3mm and teeth ratio 0.4.



(a) δ=0.3mm, τ_p=2mm, ω_t/τ_p=0.4 (b) δ=0.3mm, τ_p=3mm, ω_t/τ_p=0.4

Figure 10: Result 0.3 mm air gap length

Analysis for the teeth pitch, τ_p=2mm and teeth pitch, τ_p=3 also showed the thrust result of the air gap, δ=0.1 mm exceeds the value of thrust for the air gap, δ=0.2mm and air gap, δ=0.3mm with the value of thrust. Overall, the research result showed that the variation of the air gap length, δ has a significant effect on the thrust characteristics. The increase of air gap length leads to the reduction of thrust generated due to the larger air gap will increase the reluctance of the SRLM.

6.0 Conclusion

As a conclusion, the effects of the air gap in Switched Reluctance Linear Motor have been analysed. This Switched Reluctance linear motor is suitable for the devices that require a high precision method (Pan, Cheun & Yang, 2005). Air gap size reduction will contribute to maximizing thrust production. Thrust generation contributes to the increasing performance of SRLM motors to make them comparable to motors that use permanent magnetic as a base. The minimum target thrust produces is 40N. Based on the analysis and comparison, the best design that almost achieves the expected characteristics is by using the air gap 0.1mm, teeth pitch 3mm and teeth ratio 0.4. The current applied is 1.0A as it fulfils the design specification and the expected thrust characteristics.

References

Aerotech. (2010). *Linear motors application guide*. Retrived from https://www.aerotech.com/media/136335/linear-motors-application en.pdf

Yeo, C.K., Ghazaly, M.M., Chong, S.H., Jamaludin, I.W.& Ranom. R. (2018). Influence of materials, air gap and winding turns for a tubular linear switched reluctance actuator (TLSRA). *Journal of Telecommunication, Electronics And Computer Engineering, 10,* No. 2-2.

D. Wang, X. Du, D. Zhang and X. Wang. (2018). Design, optimization, and prototyping of segmental-type linear switched-reluctance motor with a toroidally wound mover for vertical propulsion application. *IEEE Transactions on Industrial Electronics, 65* (2),1865-1874.

Daldaban, F.& Ustkoyuncu. N. (2006). A new double sided linear switched reluctance motor with low cost. *Energy Conversion and Management, 47*(18-19),2983- 2990.

Dorrell, D.G., Knight, M.A., Popescu, M., Evans, L. & Staton, D.A. (2010). comparison of different motor design drives for hybrid electric vehicles, energy conversion congress and exposition (ECCE), *IEEE,* 3352-3359.

Gan, W. C., Widdowson, G. P, Michael S. W. Tam & Cheung, N.C. (2008). Application of linear switched reluctance motors to precision position control. *Asian Power Electronics Journal*, *2*(1), 31–36.

Garcia, J., Andrada, P., & Blanque, B. (2015). Assessment of linear switched reluctance motor's design parameters for optimal performance. *Journal of Electric Power Components and Systems*, *43*, (7) 810–819.

Higuchi, T., Yokoi, Y., Abe, T., Yasumura, N., Miyamoto, Y., & Makino, S. (2017). Design analysis of a segment type linear switched reluctance motor. *In 11th International Symposium on Linear Drives for Industry Applications (LDIA*). Osaka, Japan

Faiz, J. & Finch. J. F. (1993). Aspects of design optimisation for switched reluctance motors. *IEEE Transactions on Enegy Conversion*, *8*,(4),704-713.

Lenin, N.C. & Arumugam, R. (2010). A novel linear switched reluctance machine: analysis and experimental verification. *American Journal of Engineering and Applied Sciences*, *3*(2),433–440.

Li, X., Liu, S. & Wang, Y. (2018). Design and analysis of a new hts modular flux-switching linear machine for rail transit. *IET Electric Power Applications 12*, (9), 1256 – 1264.

Liu, Y. & Glass, G. (2013). *Effect of mesh density on finite element analysis*. SAE technical Papers.

Pan, J., Cheung, N. C., & Yang, J. (2005). High-precision position control of a novel planar switched reluctance motor. *IEEE Trans. Ind. Electron, 52*(6), 1644-1652.

Rafajdus, P. Peniak, A. Peter, D. Makys, P. & Szabo. L. (2014). Optimization of switched reluctance motor design procedure for electrical vehicles, optimization of electrical and electronic equipment (OPTIM), *IEEE,* 397 - 404.

Teixeira, V.S.C Oliviera, D. N Cunha Jr, H. & Pontes. R.S.T (2006). Linear switched reluctance motor representation using bond graph, *Digest XVI Brazillian Congress of Automatics.*

Widmer, J.D, Martin, R & Kimiabeigi, M. (2015). Electric vehicle traction motors without rare earth magnets. *Sustainable Materials And Technologies (3),* 7-13.

Zaafrane, W., Kediri, J., & Rehaoulia, H. (2013). Speed control of linear switched reluctance motor, *World Congress on Computer and Information,* 1–7.

Zhao, S. W., Wang, W X., Yang, X Y.& Cheung, N.C. (2013). analysis and design of a linear switched reluctance motor with force improvement. *In 5th International Conference on Power Electronics Systems and Applications (PESA)* (1–4). USA