学術論文

Performance Evaluation and Comparison of Switched Reluctance Cylindrical Linear Motor

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Nowadays, most of the researchers have put a lot of effort in designing the permanent magnet type of linear motor. However, due to resource problem occur recently to the permanent magnet material has led to increment of the material cost. This situation made the linear motor productivity is reduced. Because of this reason, most of linear motor manufacturers are prefer to development non-permanent magnet type to ensure product competitiveness and increase cost performance. Therefore, in this research, a switched reluctance linear motor was designed. The teeth shape has been varied in order to observed the effect to it's performance. As a result, the best model of switched reluctance linear motor with optimum teeth shape has been proposed. The performance of the model also has been compared to other similar type of linear motor and the permanent magnet type of linear motor.

Keywords: Cylindrical shape, linear motor, non-permanent magnet, switched reluctance type.

1. Introduction

Linear motor is an actuator that provide a linear motion with absence of motion translator such as belt, ball screw and gears [1,2]. This system is called as direct linear motion system. The direct linear motion system offers high flexibility of operation eliminates system limitation and reduce to total number of components used hence increase the system reliability [1-4]. The linear motor can be classified as permanent magnet type and switched reluctance type [5]. Due to superior performance of permanent magnet type especially in term of thrust density and better dynamic response made numerous of researchers put a lot of effort to develop it.

Recently, it is reported that the permanent magnet material especially sintered neodymium magnet material has facing supply chain problem. It has made the increment of it price and as well the linear motor development cost. Most of the manufacturers are currently prefer to use readily source material in order to ensure stability and competitive price [6]. Therefore, non-permanent magnet type of linear motor such as switched reluctance type is seen as an alternative. Several of researchers have discussed advantages of switched reluctance type machine. Apart of it such as robust construction, low cost in mass production, fault tolerance, high efficiency, rugged behavior, and large thrust output over very wide speed [7-10]. Furthermore, the windings are concentrated rather than distributed, making them ideal for low cost of maintenance [10]. With the continual development of power electronics and control strategies increase the reliability and effectiveness of switched reluctance type machine [11].

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In this paper, a switched reluctance linear motor was designed. The switched reluctance linear motor can be designed either in rectangular or cylindrical shape [5]. The cylindrical shape is seen has a capability to minimize the attractive force between the mover and the stator when coils are energized. This feature is due to existence of counterpart of coil compared to rectangular shape. On top of that, it also can reduce the requirement of support mechanism thus increase the thrust to size ratio [12].

The main focus of this research is to improve the performance characteristics of switch reluctance cylindrical linear motor (SRCLM). As suggested in [13] and [14], there three characteristics were used to evaluate the performance of SRCLM. There are thrust to weight ratio, F/W, thrust to volume ratio, F/V and thrust to power ratio, F/P. As report in [15], the researcher as well used ratio force to volume ratio, F/V in order to compare their findings with [13]. As a result, a switched reluctance cylindrical linear motor (SRCLM) has been designed with 123 N of average thrust, F_{ave}. It also has 45.15 N/kg of thrust to weight ratio, 0.38 x 10^6 N/m^3 of thrust to volume ratio and 2.45 N/W thrust to power ratio.

2. Basic Principle of SRCLM

2.1 Basic Structure of SRCLM

The partial structure of SRCLM is as shown in Fig. 1. The mover consists of a cylindrical shape of iron shaft with 3 mm pitch of teeth, τ_p. The stator consists of a stator yoke and coils. The stator and mover are separated by a 0.05 mm air gap. Each phase of SRCLM stator consists of 4 coils. A non-magnetic separator was used to insulate the SRCLM stator one phase to another. On top of that, the non-magnetic separators also use to maintain similar phase distance of each stator SRCLM phase. Table 1 shows the per phase coil characteristics of SRCLM.

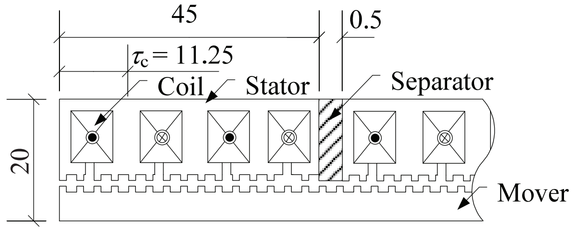


Fig. 1 Partial of SRCLM structure (unit in mm)

Table 1 Per phase coil characteristics.

No.	Parameter	Value
1	Coil turns	327
2	Coil resistance (Ω)	7.06
3	Phase resistance (Ω)	28.2
4	Phase Input power (W)	50
5	Number of coils	4

2.2 Basic Thrust Equation of SRCLM

When the coil of SRCLM is energized by certain current, I, a magnetic flux, ϕ is induced and flow from the stator to mover. The thrust of SRCLM is developed when unaligned teeth are attracted to each other until align position is achieved. The magnetic flux, ϕ can be expressed as Fourier Series as in Eq. (1) [5].

$$\phi = \phi_{DC} + \sum_{n=1}^{\infty} \phi_n \cos \frac{2\pi}{\tau_p} nx \tag{1}$$

Where ϕ_{DC} is the DC component of magnetic flux in (Wb), n is the Fourier order, ϕ_n is nth Fourier component of magnetic flux in (Wb), τ_p is teeth pitch in (m) and x is the mover displacement in (m).

The magnetic energy of SRCLM, W can be calculated using Eq. (2).

$$W = N \int_0^I \phi dI \tag{2}$$

Where W is magnetic energy in (J), N is coil turns, ϕ is the magnetic flux expression in (Wb) and I is the input current in (A).

Base on Eq. (1), the expression of magnetic energy, W can be rewritten as Eq. (3).

$$W = \sum_{n=0}^{\infty} \omega_{An} \cos \frac{2\pi}{\tau_p} nx \tag{3}$$

Where ω_{An} is the Fourier coefficient.

The thrust, F can be calculated by differentiating Eq. (3) with respect to mover displacement, x. It is shown in Eq. (4). By considering the expression of magnetic flux, ϕ as Eq. (1) and the higher order Fourier coefficients are neglected, the general thrust expression for the SCRLM can be express as Eq. (5) [5].

$$\begin{aligned} F &= \frac{dW}{dx} \\ &= -\frac{2\pi}{\tau_p} \sum_{n=1}^{\infty} n\omega_{An} \sin \frac{2\pi}{\tau_p} nx \end{aligned} \tag{4}$$

$$F = -\frac{4\pi NI}{\tau_p} \left\{ \phi \sin\left(\frac{2\pi}{\tau} nx \right) \right\} \tag{5}$$

Base on Eq. (5), despite of coil parameter such as coil turns, N and current, I, the thrust of SRCLM also depends on the teeth pitch, τ_p.

2.3 Teeth Shape Variation of SRCLM

By referring to Eq. (5), smaller teeth pitch, τ_p is used, higher thrust, F will be produced. In this paper, 3 mm has been selected for the SRCLM mover and stator teeth pitch, τ_p. The teeth width, w_d was fixed to 1.2 mm.

Instead of rectangular shape, a trapezoidal shape has been used of SRCLM teeth shape. In order to evaluate the effect of teeth shape to the SRCLM performance characteristics, the slope base length, l_1 was varied in a range of 0.0 – 0.9 mm. Fig. 2 shows the detail figure of teeth shape of SRCLM.

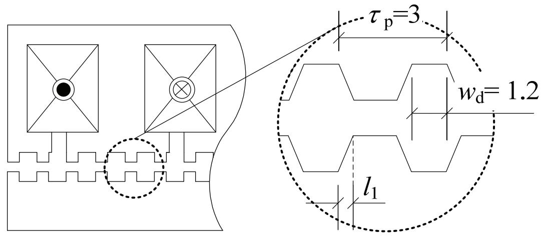
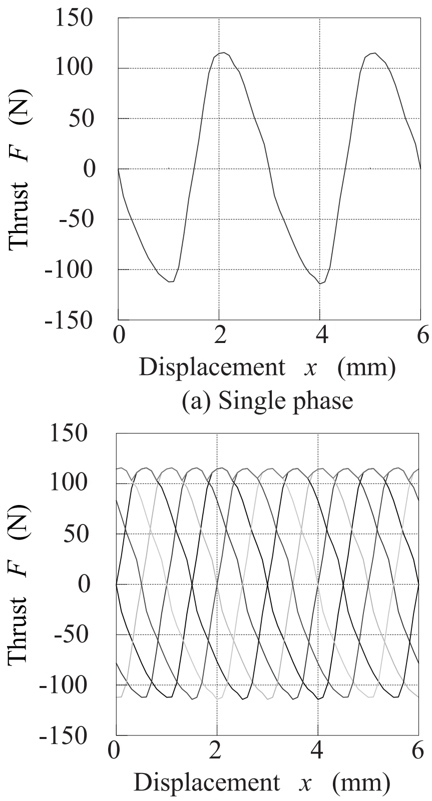


Fig. 2 Teeth shape detail of SRCLM

3. Thrust Characteristics of SRCLM

Each model of SRCLM was simulated using FEM software. Based on the FEM output, thrust characteristics of each SRCLM models was plotted. Based on the thrust characteristics, the performance characteristics of SRCLM were evaluated and the best model was identified. The thrust of SRCLM was simulated at input power, P of each phase of 50 W. The 50 W of input power, P is equivalent to 1.33 A of excitation current. Based on the observation, the value of excitation current, the magnetic saturation was not occurred. Fig. 3 shows the example of thrust characteristics of SRCLM. Base on single phase thrust characteristics as shown in Fig. 3 (a), the thrust characteristics of other stator phase of SRCLM can be derived as Fig. 3 (b).

The SRCLM is exciting by 1 phase excitation. Each phase of coil is exciting one by one. The sequence of excitation base on the phase number is 6-5-4-3-2-1. Fig. 4 shows the excitation sequence of SRCLM. Based on this excitation sequence, the six phase thrust characteristics is as shown in Fig. 5. The six phase thrust characteristics of all SRCLM models were plotted. Each model of SRCLM has been evaluated using average thrust, F_{ave}, thrust to weight ratio, F/W, thrust to volume ratio, F/V and thrust to power ratio, F/P.



(a) Single phase

(b) Six phase

Fig. 3 Thrust characteristics of SRCLM

4. Performance Comparison of SRCLM

4.1 Comparison between Similar Type of Linear Motor

The SRCLM models were evaluated using average force, F_{ave}, thrust to weight, F/W, thrust to volume, F/V and thrust to power ratio, F/P in order to search the optimum teeth shape. The teeth shape was differentiate using the slope base length, l_1.

Fig. 6 (a) shows the comparison of SRCLM average thrust, F_{ave}. It is shows that, the average thrust, F_{ave} of SRCLM is increase as the slope base length, l_1 is increase until it reach the maximum value at slope base length, l_1 equal to 0.2 mm. At the slope base length, l_1 is higher than 0.2 mm, the average thrust, F_{ave} is reducing significantly. Therefore, the best teeth shape of SRCLM is at slope base length, l_1 of 0.2 mm with average thrust, F_{ave} of 117 N.

The thrust to weight ratio, F/W and the thrust to volume ratio, F/V of SRCLM are as shown in Fig. 6 (b) and (c) respectively. By increment of slope base length, l_1 of SRCLM made increment the total volume and weight of SRCLM. However, each increment form each models is not too significant thus made these characteristics profile is not much different with the average thrust, F_{ave} profile. The highest thrust to weight ratio, F/W and thrust to volume ratio, F/V of SRCLM are 45.15 N/kg and 0.38×10^6 N/m^3 respectively.

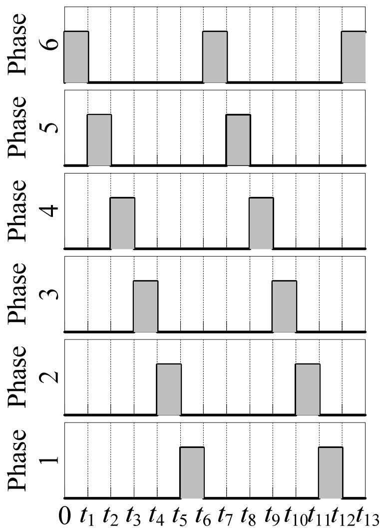


Fig. 4 Excitation sequence of SRCLM coil

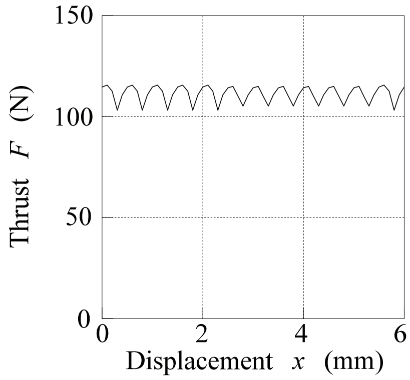


Fig. 5 Six phase characteristics of SRCLM

The input power of SRCLM was fixed to 50 W. Therefore, the profile of the thrust to power ratio, F/P is exactly the same as profile of average thrust, F_{ave} as shown in Fig. 6(d). The highest thrust to power ratio, F/P is obtained at slope base length, l_1 of 0.2 mm with value of 2.45 N/W.

All these performance characteristics of best model SRCLM is then compared to the other similar type of linear motor. In this case, the linear motor in [13], [14] and [15] were referred. Even though in [13] and [14], a linear pulse motor (LPM) were designed, however, due to similar structure to switched reluctance type of linear motor were used, these model was taken as comparison model. Furthermore, the performance of SRCLM is compared to common reluctance type performance. The comparison of performance characteristics is as shown in Table 2.

In [13], the pitch of mover has been set to 30 mm and six phase structure has been used. As a comparison, the SRCLM used the same number of phase but lower in term of the pitch. Based on Table 2, it is shown that, the performance characteristics of LPM in [13] is much lower compared to SRCLM. It is confirm with Eq. (5) that the thrust of switched reluctance motor is inversely to the pitch, τ_p.

The LPM in [14], is has better performance compared to the SRCLM in term of thrust to volume ratio, F/V and thrust to power ratio, F/P. This is due to use of permanent magnet in the LPM structure. By using the permanent magnet in the motor structure, higher thrust can be obtain over the same size hence increase the thrust to size ratio. However, the LPM in [14] is having lower in term of thrust to weight ratio, F/W compared to the SRCLM. Even though the lower pitch has been set in this LPM which 2.2 mm compared to the SRCLM, due to different of structure topology such as number of phase used, the thrust to weight ratio F/W of LPM [14] is lower than SRCLM.

In the switched reluctance linear motor (SRLM) in [15], the higher pitch has been used. The SRLM has been designed with 10 mm pitch and produced 0.25 × 10^6 N/m^3 compared to 0.38 × 10^6 N/m^3 produced by the SRCLM. However, the other performance characteristics are not reported in [15].

As shown in Table 2, the SRCLM not only having the best performance in term of thrust to weight ratio, F/W compared to other model, it also has been improved the common range of reluctance type performance. Even though the thrust to volume ratio, F/V and thrust to power ratio, F/P of the SRCLM are locates inside the common reluctance type performance range, however the value of both performances are locates near to the upper boundary of common reluctance type performance range.

4.2 Comparison of the SRCLM and Permanent Magnet Type of Linear Motor Performance.

The SRCLM performance also has been compared to permanent magnet type of linear motor (PMLM). There are three type of PMLM has been choose for comparison which are double magnet core type linear motor (DMC), permanent magnet coreless type linear motor (PMCL) and shaft motor. All of these PMLMs were selected from the commercialize PMLM from several linear motor manufacturer companies. Almost 200 PMLMs has been selected and their performance has been recorded.

The performance of PMLM normally measured by three performance indexes such as force constant, k_f, motor constant, k_m and motor constant square density, G [16]. These performance indexes were calculated using Eq. (6) - (8).

Fig. 7 shows the performance comparison between the SRCLM and the PMLMs. Apart of the three performance indexes that has been mention previously, the average thrust, F_{ave} also has been used in this comparison. All the performance indexes were plotted against their volume, V. Based on the Fig. 7, it is shown that, the SRCLM is have a capability to produce higher performance at similar volume, V compared to PMLM. The SRCLM is also seen having capability to produce higher thrust, F at smaller size and lower input power, P.

Table 2 Comparison of SRCLM with Similar Type of Motor Characteristics.

Performance	Best model SRCLM	LPM [13]	LPM [14]	SR [15]	Common Reluctance type
F/W (N/kg)	45.15	15.00	43.20	-	20 - 30
F/V (× 10^6 N/m^3)	0.38	0.075	0.43	0.25	0.06 – 0.40
F/P (N/W)	2.45	1.38	5.10	-	0.5 – 3.0

$$k_f = \frac{F}{I} \tag{6}$$

$$k_m = \frac{F}{\sqrt{P}} \tag{7}$$

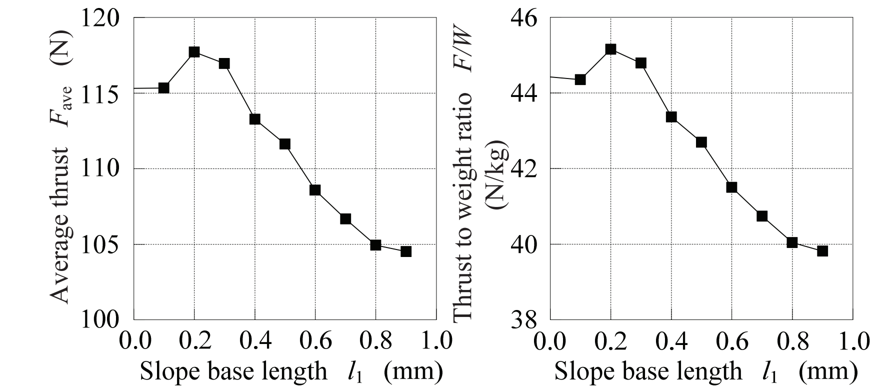
$$G = \frac{F^2}{PV} \tag{8}$$

Where k_f is the force constant in (N/A), k_m is the motor constant in (N/W$^{1/2}$), P is the input power in (W), G is the motor constant square density in (F^2/Wm^3) and V is the volume in (m^3).

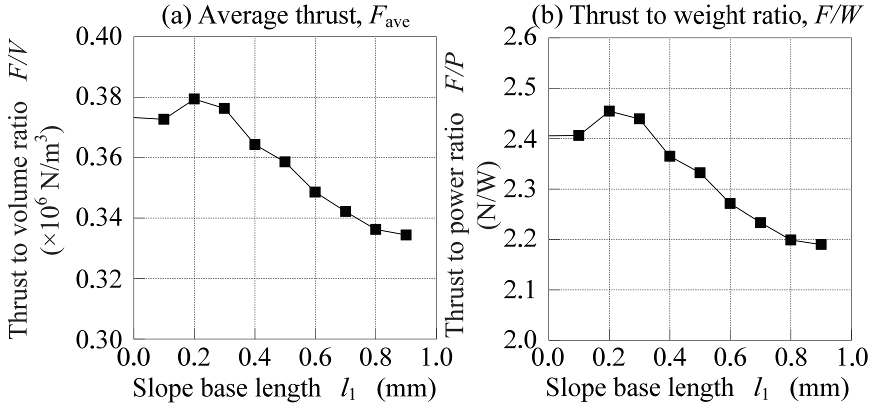
5. Conclusion

In this paper, a non-permanent magnet type of linear motor was designed. The aimed of this paper is to improve the performance of switched reluctance cylindrical linear motor (SRCLM). From the analysis results, the following conclusions are obtained.

1. The teeth pitch, τ_p is playing a significant role in increase the thrust, F. as can be seen from the thrust comparison of the SRCLM with the LPM in [13].
2. The SRCLM has improved the performance of common reluctance type in term of thrust to weight ratio, F/W.
3. Even though the other two performance characteristics of SRCLM which are thrust to volume ratio, F/V and thrust to power ratio F/P are located in common reluctance type range performance, however its located near to the boundary of the range.
4. The SRCLM is capable to produce high thrust, F base on the comparison it performance indexes to the PMLM.

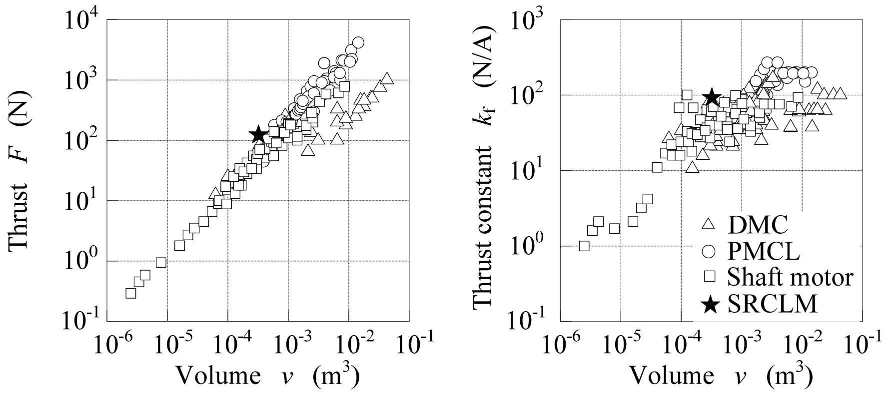


(a) Average thrust, F_{ave}　(b) Thrust to weight ratio, F/W

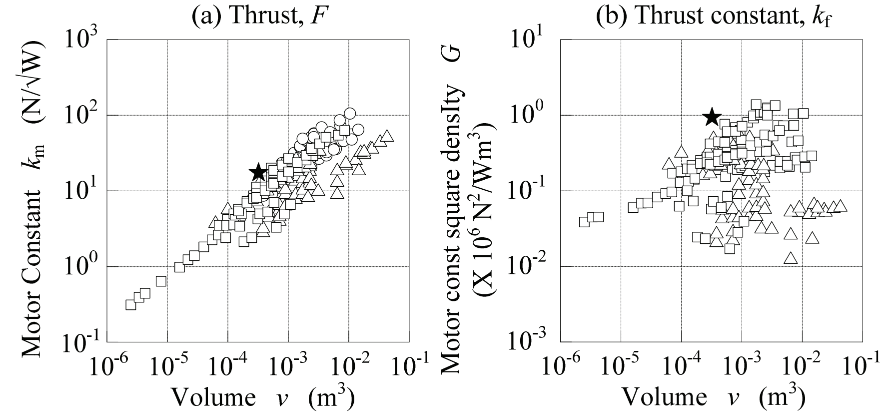


(c) Thrust to volume ratio, F/V　(d) Thrust to power ratio, F/P

Fig. 6 Performance comparison of SRCLM



(a) Thrust, F　(b) Thrust constant, k_f



(c) Motor constant, k_m　(d) Motor constant square density, G

Fig. 7 Comparison of SRCLM and PMLMs performance

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