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Analysis of Linear Machine by Parameter Study using Equivalent Magnetic Circuit and FEA

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This study proposes an analytical approach by optimum process that is generalized by number of phases, magnet, and pole-pair of linear machines based on a physical magnetic circuit model. The linear machine increases the force output of the machine due to generation of the magnetic field created by the armature winding. There is a strong attractive force between the iron-core armature and the permanent magnet. Therefore, this paper deals not only with one-phase systems by the number of magnet and pole pairs but also two-phase machines in linear machines. All this is carried out for optimum process using geometric parameters based on analytical electromagnetic field research. The best structure for optimum design is selected by a parameter study and it is accomplished with 2-D finite element analysis. The object function and design variables for this parameter study by constraints are chosen for practical and effective design of the machine. Eventually, it suggests new design rules based on optimal design through parameter study. The proposed methods allow us to draw a very important design rule, as a result it can be provided to less time of the machine design and analysis.

Keywords : constraint, design variable, equivalent magnetic circuit, magnetic energy, object function, parameter study

1. Introduction

In a flat type of linear machine, the coil windings are inserted into a steel structure to create the coil assembly. There is a strong attractive force between the armature iron-core and the permanent magnet requiring a solid support structure [1]. Achieving linear motion with a machine that needs no gears, couplings or pulleys makes sense for many applications, where unnecessary components that diminish performance and reduce the life of a machine can be removed. However, there will be end effect related cogging forces due to the finite armature length. In effect, these forces cause noise and vibrations. Consequently, numerous methods can be used to minimize cogging and end effects by utilizing the end effect compensators, semi-closed slots, or magnetic slot wedges, varying the length of the airgap, magnet shape skewing or chamfering magnet length optimization etc. [2]. Therefore, optimizing the magnet or armature iron-core length ensures that the end effect cogging force components can cancel each other. Also, shaping or smoothing the axial end corners also can significantly reduce the cogging force due to the axial end-effects. We will be able to investigate every characteristic following number of phases, magnet, and pole pairs as below:

- Type I: Single-phase system with two magnets and two pole-pairs
- Type II: Two-phase system with one magnet and one pole-pair
- Type III: Two-phase system with one magnet and one

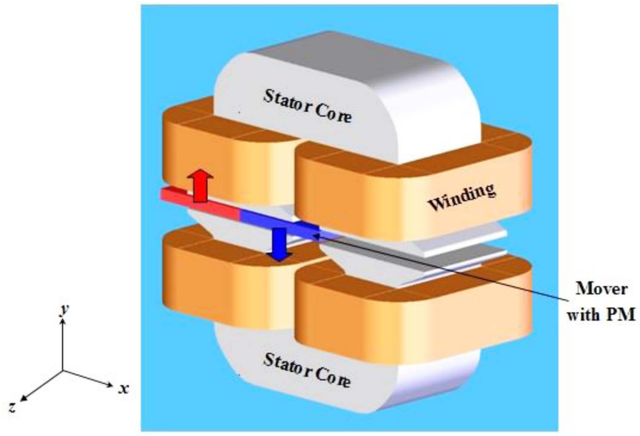

Fig. 1. (Color online) Linear Machine.

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pole-pair

As the configuration example shown in Fig. 1, linear machine with magnet mover consists of three parts; two stators contain the winding, and the other is the mover with the magnet which is magnetized in *y*-direction. The flux linked with circular wound coils changes periodically to produce the electromotive force. The upper and lower part that is marked by gray-color is the stator iron-core. No iron-core required in the mover, so this type has the smallest moving mass allowing high accelerations.

2. Comparison of Type I, II, and III

• Type I: This model has a relatively low leakage flux because there are stator iron cores in upper and lower part guiding the magnetic flux. Besides, it is suitable for short stroke application due to divided two magnets which magnetized perpendicular to the stator winding. Nevertheless, it is inevitable to avoid leakage flux since the total length of magnet is longer than that of stator teeth.

• Type II: Although this type has an advantage of small volume compared with other linear machine models, this model is inefficient in terms of structure. The reason is that it is very short or little magnetic flux path which runs through stator iron core and magnet as mover. It has a serious leakage flux structurally because the magnet of mover is only magnetized in one vertical direction. This generates leakage flux at opposite end part even if current is excited to convert of phase switch in accordance with mover position. As a result, this model should be two-phase system and it has become more complex and increasingly specialized.

• Type III: It consists of one longer magnet as mover, in which magnetic flux can be increased effectively. But leakage flux by armature winding is approximately 41.75 [%] bigger in comparison with type I. On the contrary, the effective magnetic flux of opposite end part to interact between magnet and stator teeth is nearly zero when the magnet of mover is aligned.

After considering all the types, we will investigate Cartesian model Type I with respect to force and magnetic energy by equivalent magnetic circuit method. First of all, it should be considered from geometrical structure for low leakage flux and high energy density. Based on their evaluation, it will be accomplished for optimal design by geometrical parameters.

3. Analytical Calculation

The geometric arrangement is important for proper operation of magnet mover and optimization process by parameter study. In Fig. 3, τ_p represents the aggregate of width of stator tooth, w_t and length of slot-opening, b_0. It requires the calculation of width of magnet which is closely connected with the moving element in this system. The width of the magnet, w_m should be satisfied that it must be longer than $1/2 \cdot \tau_p$.

It is analyzed in two different methods which are

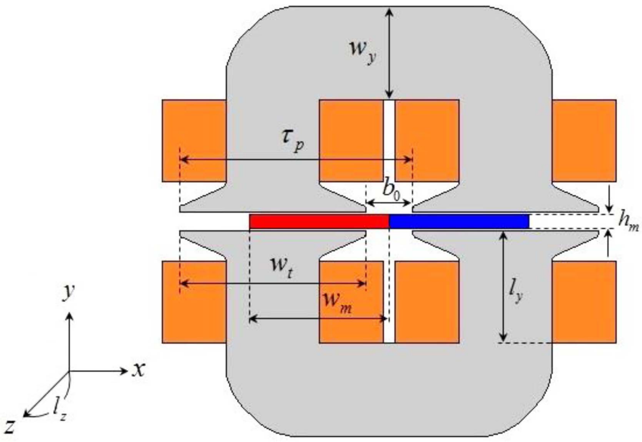


Fig. 3. (Color online) Cross-section of Linear Machine.

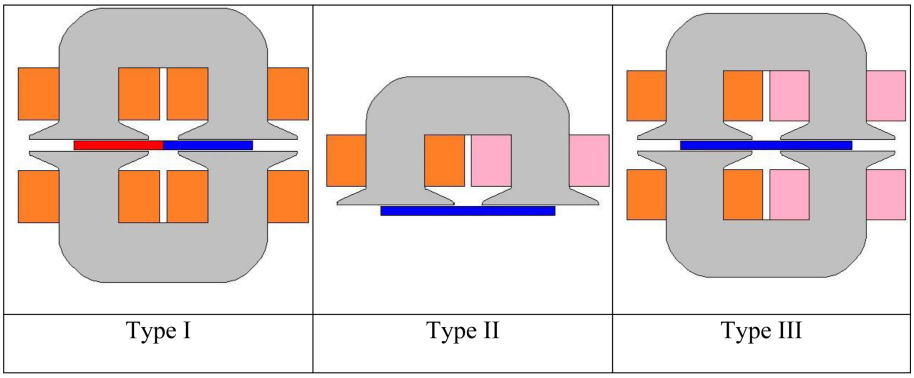


Fig. 2. (Color online) Study Models.

accomplished using equivalent magnetic circuit and optimization by parameter study [3]. The evaluation of electric characteristics by geometric factors such as w_t, w_m, w_v, l_y, h_m and b_0 will be discussed in Optimal Process and Optimization in chapter 4 and 5. In order to evaluate by an equivalent magnetic circuit, it is necessary to detail the magnetomotive forces of stator and magnet respectively.

$$\Theta_a = N_c \cdot I \tag{1}$$

$$\Theta_m = \frac{B_{rem} \cdot h_m}{\mu_0 \cdot \mu_r} \tag{2}$$

where, N_c, I, and B_{rem} indicates a number of coil turns, excited current, and residual magnetic flux density (remanence) of magnet, respectively.

3.1. Type I

Fig. 4 shows a configuration of type I and then equivalent magnetic circuit for magnetic energy calculation [4]. Analytical expression for the force and magnetic energy calculation is as follows.

$$R_\delta = \frac{1}{\mu_0} \cdot \frac{2 \cdot \delta}{w_t \cdot l_z} \tag{3}$$

$$R_m = \frac{1}{\mu_0} \cdot \frac{h_m}{\mu_r} \cdot \frac{1}{w_t \cdot l_z} \tag{4}$$

$$R_\sigma = \frac{1}{\mu_0} \cdot \frac{1}{l_z} \cdot \frac{2 \cdot \delta}{\left(\frac{w_t \cdot w_m}{2}\right)} + \frac{1}{\mu_0} \cdot \frac{\pi}{2} \cdot \frac{1}{l_z} \cdot \frac{1}{\ln\left(\frac{\frac{w_t - w_m}{2}}{2 \cdot \delta + h_m}\right)} + R_{me} + R_{mm} \tag{5}$$

where, R_δ and R_m represents a reluctance at airgap and magnet, respectively. The R_σ means the sum of the leakage reluctances which interacts between armature iron-core and magnet, is generated between the magnets expressed by R_{mm}, and is caused in magnet edges expressed by R_{me}. In a magnet pole pair, a leakage flux model for PM machines has been developed. For PM machines, the portion of the magnet-to-magnet leakage has been well modeled using the circular-arc or straight-arc permeance model [5]. To obtain an analytical expression for the leakage flux in terms of the magnetic material properties and the machine dimensions, some assumptions are needed to simplify the problem; the reluctances associated with iron are negligible. So, it can be expressed by permeance as equation (6) through Fig. 5.

$$P_{mm} = \frac{1}{R_{mm}} = \Sigma \frac{\mu_0 \cdot l_z \cdot dx}{\lim\limits_{y=0} \frac{1}{y} + \pi \cdot x} = \int_0^\delta \frac{\mu_0 \cdot l_z}{\lim\limits_{y=0} \frac{1}{y} + \pi \cdot x} dx$$
$$= \frac{\mu_0 \cdot l_z}{\pi} \cdot \ln\left(1 + \frac{\pi \cdot \delta}{\lim\limits_{y=0} \frac{1}{y}}\right) \tag{6}$$

Meanwhile, the reluctance caused by magnet leakage flux in edge part of mover magnet can be also obtained by calculating its permeance [5]. The circular permeance model is one of the most satisfactory techniques for

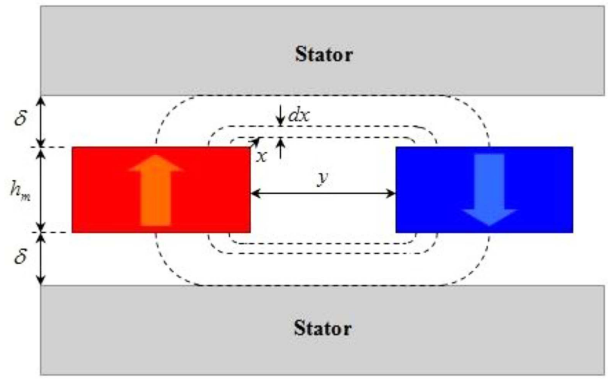


Fig. 5. (Color online) Leakage flux between magnets.

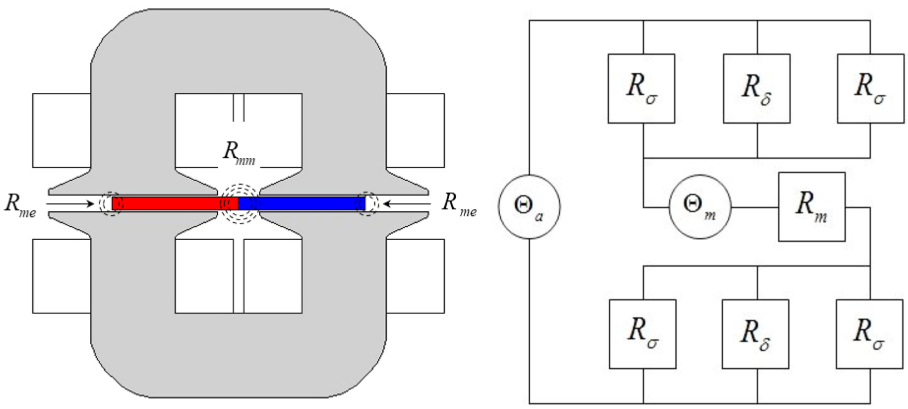


Fig. 4. (Color online) Type I with assembly.

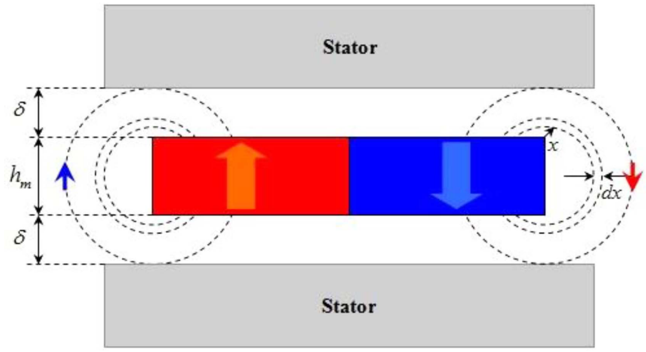


Fig. 6. (Color online) Leakage flux in magnet edge.

modeling flux flowing in an airgap as depicted in Fig. 6. The fringing permeance P_{me} is an infinite sum of differential width permeance, each of length $h_m + 2\pi x$.

$$P_{mm} = \frac{1}{R_{mm}} = \Sigma \frac{\mu_0 \cdot l_z \cdot dx}{\lim\limits_{y=0} \frac{1}{y} + \pi \cdot x} = \int_0^{\delta} \frac{\mu_0 \cdot l_z}{\lim\limits_{y=0} \frac{1}{y} + \pi \cdot x} dx$$

$$= \frac{\mu_0 \cdot l_z}{\pi} \cdot \ln\left(1 + \frac{\pi \cdot \delta}{\lim\limits_{y=0} \frac{1}{y}}\right) \tag{7}$$

Analytical expression for the force and magnetic energy calculation are as follows.

$$\varphi_{a\delta} = \frac{\theta_a \cdot (R_\sigma + R_m)}{(2 \cdot R_\delta + \cdot R_\sigma) \cdot R_m + 2 \cdot R_\delta \cdot R_\sigma} \tag{8}$$

$$\varphi_{a\sigma} = \frac{\theta_a \cdot (R_\delta + R_m)}{(2 \cdot R_\delta + \cdot R_\sigma) \cdot R_m + 2 \cdot R_\delta \cdot R_\sigma} \tag{9}$$

$$\varphi_{m\delta} = \frac{\theta_m \cdot R_\sigma}{(2 \cdot R_\delta + \cdot R_\sigma) \cdot R_m + 2 \cdot R_\delta \cdot R_\sigma} \tag{10}$$

$$\varphi_{m\sigma} = \frac{\theta_m \cdot R_\delta}{(2 \cdot R_\delta + \cdot R_\sigma) \cdot R_m + 2 \cdot R_\delta \cdot R_\sigma} \tag{11}$$

A magnetic network by Kirchhoff Law can be expressed in analogy through electrical circuit theory. By simply equivalence, the average force and force density is derived by using difference of maximum and minimum magnetic energy. The flux equations above are obtained by calculating and the equivalent magnetic circuit in aligned (maximum) and unaligned (minimum) position, respectively.

$$W_{\max} = 2 \cdot (\phi_{a\delta} + \phi_{m\delta})^2 \cdot R_\delta + (\phi_{a\sigma} - \phi_{m\sigma})^2 \cdot R_\sigma + (\phi_{a\delta} - \phi_{a\sigma} + \phi_{m\delta} + \phi_{m\sigma})^2 \cdot R_m \tag{12}$$

$$W_{\min} = 2 \cdot (\phi_{a\delta} - \phi_{m\delta})^2 \cdot R_\delta + (\phi_{a\sigma} - \phi_{m\sigma})^2 \cdot R_\sigma + (\phi_{a\delta} - \phi_{a\sigma} - \phi_{m\delta} - \phi_{m\sigma})^2 \cdot R_m \tag{13}$$

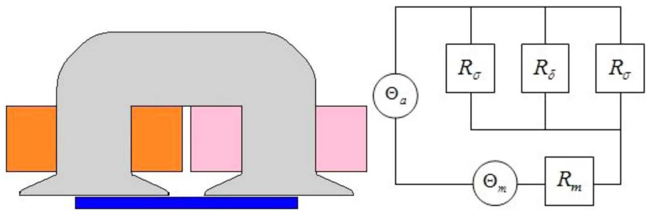


Fig. 7. (Color online) Type II with assembly.

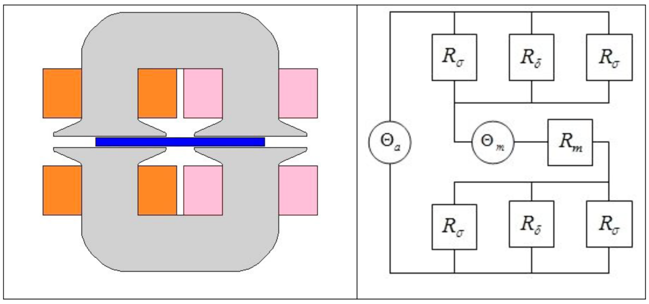


Fig. 8. (Color online) Type III with assembly.

3.2. Type II

This topology is composed of perpendicular magnetized one-magnet mover and one-side armature iron-core. The organization and its equivalent magnetic circuit are given in Fig. 7.

$$R_\delta = \frac{1}{\mu_0} \cdot \frac{\delta}{w_t \cdot l_z} \tag{14}$$

The R_m of type II is identical with the equation (4) of type I.

$$R_\sigma = \frac{1}{\mu_0} \cdot \frac{1}{l_z} \cdot \frac{\delta}{\left(\tau_p - \frac{w_m}{2}\right)} + \frac{1}{\mu_0} \cdot \frac{\pi}{2} \cdot \frac{1}{l_z} \cdot \frac{1}{\ln\left(\frac{\tau_p - \frac{w_m}{2}}{\delta}\right)} + R_{me} \tag{15}$$

$$\varphi_{a\delta} = \frac{\theta_a \cdot \left(\frac{R_\sigma}{2} + R_m\right)}{R_\delta \cdot \frac{R_\sigma}{2} + \left(\frac{R_\sigma}{2} + R_\delta\right) \cdot R_m} \tag{16}$$

$$\varphi_{a\sigma} = \frac{\theta_a \cdot \left(\frac{R_\delta}{2} + R_m\right)}{R_\delta \cdot \frac{R_\sigma}{2} + \left(\frac{R_\sigma}{2} + R_\delta\right) \cdot R_m} \tag{17}$$

$$\varphi_{m\delta} = \frac{\theta_m \cdot \frac{R_\sigma}{2}}{R_\delta \cdot \frac{R_\sigma}{2} + \left(\frac{R_\sigma}{2} + R_\delta\right) \cdot R_m} \tag{18}$$

$$\varphi_{m\sigma} = \frac{\theta_m \cdot R_\delta}{R_\delta \cdot \frac{R_\sigma}{2} + \left(\frac{R_\sigma}{2} + R_\delta\right) \cdot R_m} \tag{19}$$

$$W_{\max} = \frac{1}{2} \cdot (\phi_{a\delta} + \phi_{m\delta})^2 \cdot R_\delta + \frac{1}{4}(\phi_{a\sigma} - \phi_{m\sigma})^2 \cdot R_\sigma + \frac{1}{2}(\phi_{a\delta} - \phi_{a\sigma} + \phi_{m\delta} - \phi_{m\sigma})^2 \cdot R_m \tag{20}$$

$$W_{\min} = \frac{1}{2} \cdot (\phi_{a\delta} + \phi_{m\delta})^2 \cdot R_\delta + \frac{1}{4}(\phi_{a\sigma} + \phi_{m\sigma})^2 \cdot R_\sigma + \frac{1}{2}(\phi_{a\delta} - \phi_{a\sigma} + \phi_{m\delta} - \phi_{m\sigma})^2 \cdot R_m \tag{21}$$

The structure has inefficient flux paths to pass flux, in other words, the leakage flux is significantly large. Thus, it should be supported structurally such at least two magnets for effective operation.

3.3. Type III

This system has a hybrid structure [6] of type I and II as shown in Fig. 8; the armature from type I and the magnet mover from type II. Analytical formula for solving equivalent magnetic circuit is as in the following.

The R_δ and R_m of type III is identical with the equation (3) and (4) of type I, respectively.

$$R_\sigma = \frac{1}{\mu_0} \cdot \frac{1}{l_z} \cdot \frac{\delta}{\left(\tau_p - \frac{w_m}{2}\right)} + \frac{1}{\mu_0} \cdot \frac{\pi}{2} \cdot \frac{1}{l_z} \cdot \frac{1}{\ln\left(\frac{\tau_p - \frac{w_m}{2}}{\delta}\right)} + R_{me} \tag{22}$$

$$\varphi_{a\delta} = \frac{\theta_a \cdot \left(\frac{R_\sigma}{2} + R_m\right)}{R_\delta \cdot R_\sigma + \left(\frac{R_\sigma}{2} + R_\delta\right) \cdot R_m} \tag{23}$$

$$\varphi_{a\sigma} = \frac{\theta_a \cdot \left(\frac{R_\delta}{2} + R_m\right)}{R_\delta \cdot R_\sigma + \left(\frac{R_\sigma}{2} + R_\delta\right) \cdot R_m} \tag{24}$$

$$\varphi_{m\delta} = \frac{\theta_m \cdot \frac{R_\sigma}{2}}{R_\delta \cdot R_\sigma + \left(\frac{R_\sigma}{2} + R_\delta\right) \cdot R_m} \tag{25}$$

$$\varphi_{m\sigma} = \frac{\theta_m \cdot R_\delta}{R_\delta \cdot R_\sigma + \left(\frac{R_\sigma}{2} + R_\delta\right) \cdot R_m} \tag{26}$$

$$W_{\max} = (\phi_{a\delta} + \phi_{m\delta})^2 \cdot R_\delta + \frac{1}{2}(\phi_{a\sigma} - \phi_{m\sigma})^2 \cdot R_\sigma + \frac{1}{2}(\phi_{a\delta} + \phi_{a\sigma} + \phi_{m\delta} - \phi_{m\sigma})^2 \cdot R_m \tag{27}$$

$$W_{\min} = (\phi_{a\delta} - \phi_{m\delta})^2 \cdot R_\delta + \frac{1}{2}(\phi_{a\sigma} + \phi_{m\sigma})^2 \cdot R_\sigma + \frac{1}{2}(\phi_{a\delta} - \phi_{a\sigma} - \phi_{m\delta} - \phi_{m\sigma})^2 \cdot R_m \tag{28}$$

3.4. Force Calculation

The total magnetic energy of all types can be obtained by difference between maximum and minimum magnetic energy. Using the formula, average force (F_{ave}) and force density (F_{den}) is given as below equations.

$$F_{ave} = \frac{W_{\max} - W_{\min}}{\tau_p} \tag{29}$$

$$F_{den} = \frac{F_{ave}}{2 \cdot \tau_p \cdot l_z} \tag{30}$$

4. Optimal Process

In a general concept for the optimum design, it is to minimize of time and cost for design process. The conventional design process can lead to uneconomical designs and can involve a lot of calendar time. In these cases, the designer would find it difficult to decide whether to increase or decrease of the size of a particular structural element to satisfy the constraints. The optimum design process forces the designer to identify explicitly a set of design variables, an objective function to be optimized, and the constraint functions for the system [7]. Thus, the best approach would be an optimum design process that is aided by the parameter study of design variables. Any modeling system has a mechanism that allows you to perform investigation of the model's reaction to its parameters. In simple words, parameters are any numerical quantity that characterizes a given some aspect of the model.

In this study, the force maximization is selected as the main aspect under given conditions which are by design variables. Evaluation of electrical characteristics of linear machine depends essentially on the geometry design

Table 1. Object function, Design variables, and Constraints.

-	Symbol	Initial Value	Constraints
Design Variables	h_m [mm]	5	$1 \le h_m \le 16$
	w_m [mm]	22	$20 \le w_m \le 27$
	w_y [mm]	28	$18 \le w_y \le 36$
	l_y [mm]	16	$8 \le l_y \le 24$
	b_0 [mm]	4	$2 \le b_0 \le 10$
	w_t [mm]	25	$24 \le w_t \le 33$
Object Function	Force [N]	235	-
Flux Density	B [T]	-	1.6-1.7

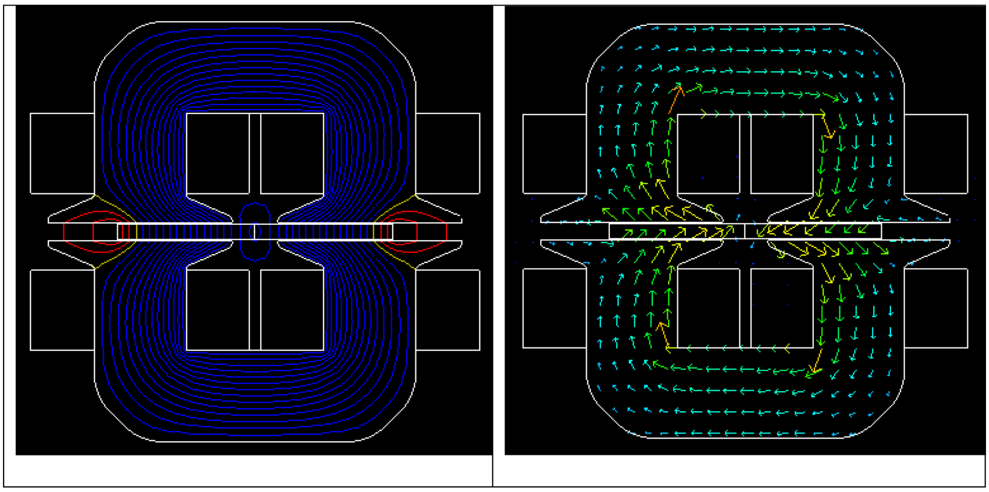


Fig. 9. (Color online) Magnetic flux characteristics of Optimum Model.

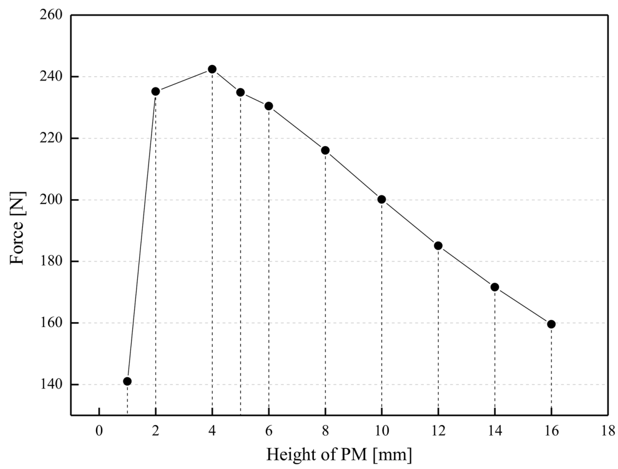
parameters. The geometric design parameters are relative to the structural factors, especially height of magnet (h_m), width of magnet (w_m), width of yoke (w_y), length of yoke (l_y), length of slot-opening (b_0), and width of tooth (w_t). Based on the above mentioned description, the equivalent magnetic circuit considering leakage reluctances is used to calculate the force as object function. The parameter study for optimal process is performed using Type I which has an advantage in the effective magnetic flux.

First of all, it is very important to decide an initial value and the constraints of each design variables because an optimal result could be changed by them. The flux density in armature iron-core should be not more than 1.6-1.7[T]. The selected design variables have a significant effect on characteristics in linear machine. Moreover, proper choice of initial values makes it more easily and rapidly to access the optimal result. If it is unreliable initial values, it brings about wrong results. An initial value should be selected considering electrical and geometrical properties under reasonable constraint condition.

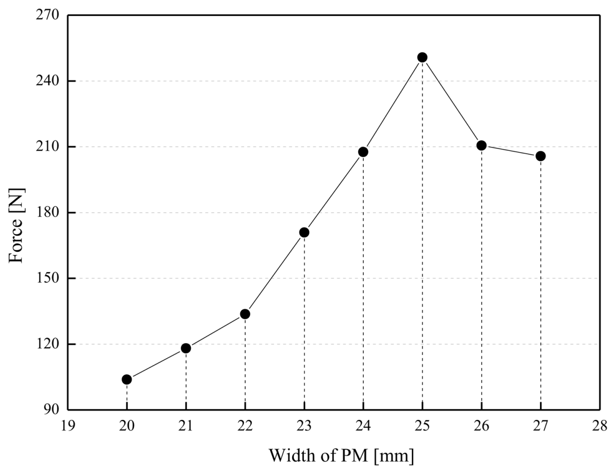
Fig. 9 shows a typical magnetic field line and vector plot in a cross-section view of the overall model. We discuss optimization process through the parameter study of each design variables. It will be investigated that each design variables affects the object function and is also affected by the constraint conditions.

4.1. Height of Magnet: h_m

An electromagnet force made from coils is usually called the 'force constant' (But it would be more accurate to refer to it as the force-current relation because it is significantly affected by many factors). Due to interaction such electromagnetic force and force by magnet, it needs optimal selection of magnet height. It can be given by parameter study as Fig. 10(a); we can observe aspect of force profile. Especially, when the height of magnet is



(a) Height of PM



(b) Width of PM

Fig. 10. Force Characteristics by Geometrical Form of PM.

4[mm], the value of force is approximately 245[N] and it is the biggest under the given constraint, $1[\mathrm{mm}] \le h_m \le 16[\mathrm{mm}]$. If the height is larger than 4[mm], the force is decreasing slowly. For this effect mainly saturation is responsible.

4.2. Width of Magnet: w_m

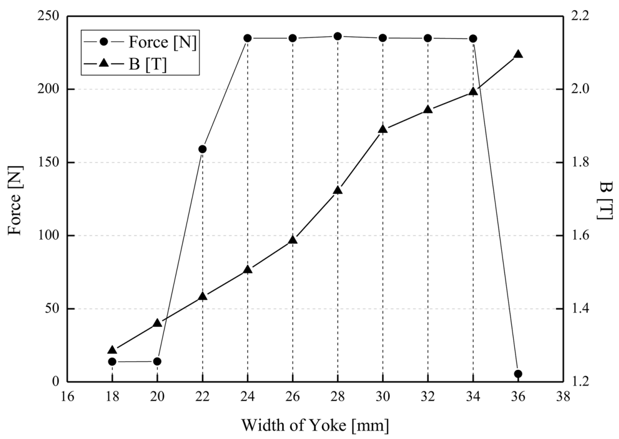
The effect of the width of magnet should be viewed in parallel to the height of magnet. The dimension of the magnet affects the flux density in armature iron-core and it also influences on the force. Fig. 10(b) shows the force characteristic curve by width of magnet. Its minimum size is not less than pole pitch, τ_p, in that magnet as moving part shall be operated. As a result of the analysis, it brings into a satisfying result when a width of magnet is 25[mm] and the flux density of armature iron-core has almost 1.6[T] under given whole constraints.

4.3. Width of Yoke: w_y

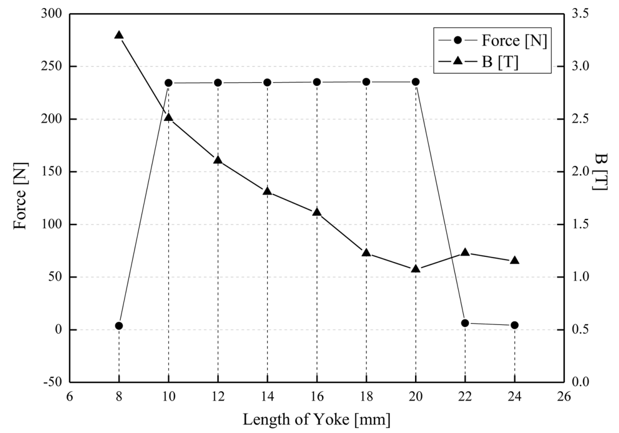
The width of yoke is an essential factor in making decision of geometric size in a 2-D plane. This marked design variable enables magnetic flux to flow the least distance. It will be inefficient due to the increasing of the force to weight ratio if the width of yoke exceeds 34[mm]. On the contrary, if the width of yoke is shorter below 24[mm], it needs higher armature current to keep a maximize force. In this case, the magnetic flux density will saturate the armature iron-core, besides demagnetization phenomenon could occur in the magnet. This is converted to heating and will lead to hysteresis loss. There is nothing to considerable change between 24[mm] to 34[mm] as shown Fig. 11(a). Satisfying flux density as constraint in armature iron-core, it is important to extend the force of object function. As a result, the 28[mm] is chosen to be optimal value for the width of yoke.

4.4. Length of Yoke: l_y

Subsequently, a research about length of yoke is performed. There are two curves for the force and the flux density in Fig. 11(b). The graph of force in length of yoke is almost similar from 10[mm] to 20[mm]. Thus, we cannot be sure to decide about the length of yoke without



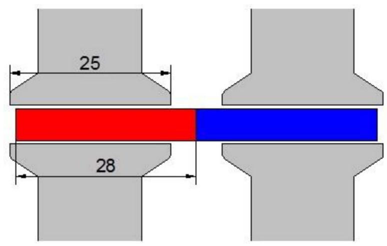
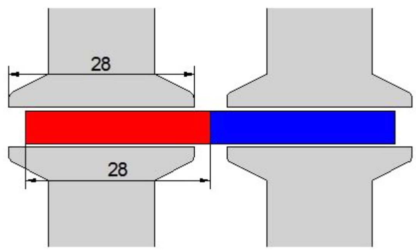
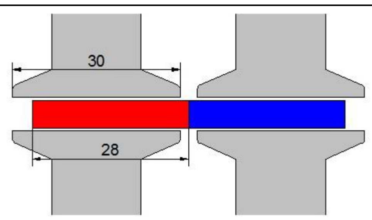
(a) Width of Yoke



(b) Length of Yoke

Fig. 11. Force and Flux-density Characteristics by Geometrical Form of Yoke.

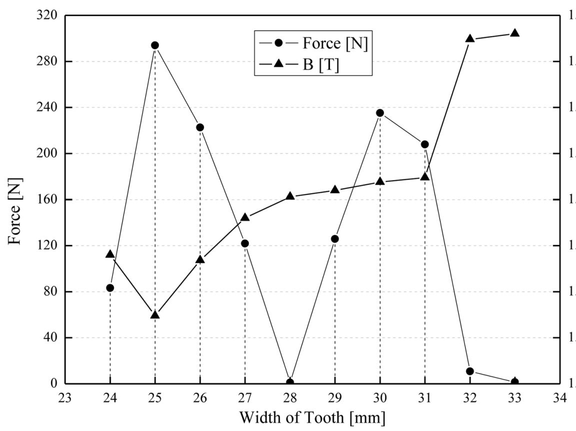
Table 2. (Color online) Configurations of width of teeth at constant width of magnet.


25[mm]

28[mm]

30[mm]

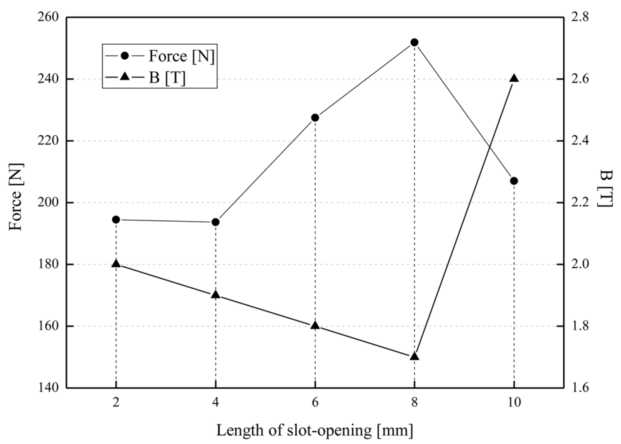
constraint. Meanwhile, the curve of flux density shows that there can be wide difference in length of yoke. The focus value of flux density is drawn about 1.6[T] in armature iron-core. Eventually, optimal point is in the best 16[mm] of length of yoke corresponding to the force maximization under the given constraint.

4.5. Width of Teeth: w_t

The width of teeth ranges from 24[mm] to 33[mm]. As shown Fig. 12(a), force profile shows a symmetrical aspect around the 28[mm] of width of teeth. The reason that the force value is almost zero at 28[mm] is the equality of teeth width and width of magnet. In this parameter study, the width of magnet is used in fixed position of 28[mm]. It has the maximum value when width of teeth is 25[mm] and 30[mm], especially considering in terms of only force values. Although the maximum force value is at the 25[mm] teeth width under given constraints, the flux density value is much lower than 1.6-1.7[T]. This is inefficient on a basic energy conversion principle, therefore we prefer the optimal point at



(a) Width of Teeth



(b) Length of Slot-opening

Fig. 12. Force and Flux-density Characteristics by Geometrical Form of Teeth and Slot-opening.

30[mm].

There are some configurations by width of teeth in critical point in Table 2.

4.6. Length of Slot-opening: b_0

With regard to length of slot-opening, the coil winding process should be taken into account and the minimization of detent force. Its initial length is fixed to 2[mm] at least considering the insertion wound coils. Thus, a geometrical dimension is important to get an optimum result by minimizing cogging force with proper balance between width of tooth and length of slot-opening. In Fig. 12(b), we can find optimal point when the length of slot-opening is 8[mm].

5. Optimization

The Table 3, presents the result of parameter progress about design variables within each constraint. Optimal values of height of magnet, width of magnet, width of yoke, length of yoke and length of slot-opening is almost alike or coincide in initial values.

This study by the optimal process is assumed as the following;

Table 3. Comparison result between initial and optimal design.

-	Symbol	Initial Value	Optimization
Design Variables	h_m [mm]	5	4
	w_m [mm]	22	25
	w_y [mm]	28	28
	l_y [mm]	16	16
	b_0 [mm]	4	8
	w_t [mm]	25	30
Object Function	Force [N]	235	250
Flux Density	B [T]	1.4-2.0	1.6-1.7

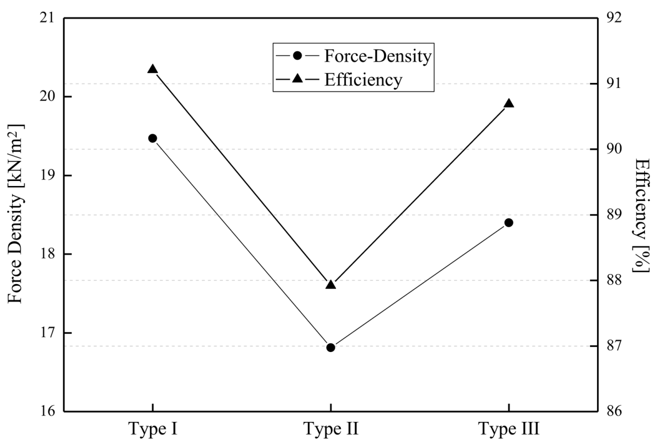


Fig. 13. Force density and efficiency.

• Armature reaction and demagnetization of the PM edge is ignored.

• Usually, an object function is composed of more than one parameter. However, the optimization study is achieved by 6 proposed variables and their constraints.

6. Conclusion

This study has investigated the characteristics of three different topologies in linear machine. It was analyzed by two methods: equivalent magnetic circuit and optimization process. A value of force density using magnetic energy calculation is the biggest in type I. The reason is that it allows efficient flow of magnetic flux structurally. In respect to the efficiency, type I is also the highest on account of lower leakage flux compared to another type II and III. Whereas type II has an inefficient magnetic flux path; consequently, the force density and efficiency are the lowest of among the types. In virtue of effective magnetic flux paths, type I shows better results than type II and III in all of force density and electrical characteristics.

The parameters study through design variables is one of the optimal processes, which benefits from good starting guesses. The choice of these parameters should be determined by factors influencing the object function. Also, the constraint such as satisfaction of critical value of flux density can be added for the practical design in the process of optimization. Generally, the optimization problems are best solved rapidly and trustfully when a proper selection of initial values is performed, and the number of independent design variables are smaller. It will be helpful to investigate various topologies which are not only linear machine.

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