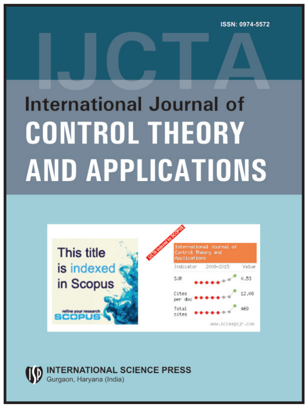

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Design and Optimization of Iron Core Linear Synchronous Motor

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Abstract: This paper presents the modeling and design of an iron core linear synchronous motor (LSM) structure based on the conventional coreless LSM that is available in the market. A double layer coil iron core LSM is designed and see whether such design concept is viable in increasing the required thrust force. Based on the design concept, the LSM can be further optimized such the thrust force produced can be increased with minimum usage of power.

Keywords: Iron core; linear synchronous motor.

1. INTRODUCTION

The demand of linear synchronous motor (LSM) has grown tremendously over the year especially in industry which focuses on automation and numerical control systems where linear occurrence of industrial machineries are necessary [1-2]. Such phenomenon is due to the ability to generate thrust force directly and at the same time provides several advantages over rotary-to-linear system due to its accuracy in positioning and controlling, simplicity and efficiency [2]. In order to cope with extreme velocity control, positioning and quick response of the assembly lines for factory, LSM is often designed and manufactured in various types such as coreless LSM or Iron core LSM which are the more common one [3]. In this context, coreless LSM is often used as precision machine tool due to its high speed performance, driving force, quick response between acceleration and deceleration and positioning. Coreless LSM generally produces small thrust than conventional iron core LSM and has smaller thrust variations which results in small ripple rate as there is no cogging produced in a coreless LSM. An iron core LSM generates a much higher thrust at the start of the translation and reduces throughout the displacement. That being said, an iron core LSM is suitable to be used in applications which require high starting thrust initially such as the lift system [4-5]. In this paper, an iron core LSM is modeled and designed based on the conventional coreless LSM to cope with applications which requires high starting thrust initially. Then, the designed iron core LSM is further optimized by adding double layer of coil to significantly increase the starting thrust of the iron core LSM. That being said, this paper illustrates the proposed motor structured and its optimization on the generation of thrust force. In this context, the consumption of electric power is also taken into consideration while analyzing the overall performance of the proposed iron core LSM.

2. PRINCIPLE AND ANALYTICAL ANALYSIS OF LSM

The fundamental principle applied in linear motor is similar the rotary machine. The major difference between this two motor is that linear dimension and displacements replace the angular rotation of the circular motor. In this context, the torque which is generated in rotational motion is replaced by thrust force in the event of linear motion. On the other hand, the commutation cycle is distance between two consecutive pole pairs in linear motion instead of 360 degrees in rotational motion [6]. Figure 1 and Figure 2 illustrate principles of circular motor and linear motor respectively.

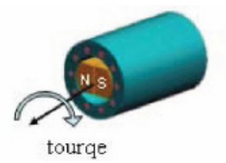

Figure 1: Principles of linear motor [2]

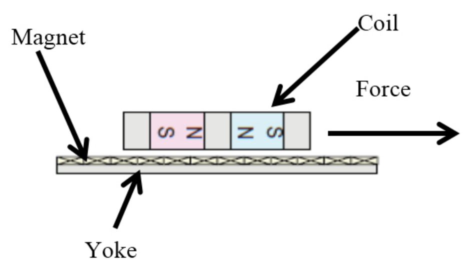

Figure 2: Principles of rotational motor [2]

Linear motor is generally classified as the mobile and stationary part where the mobile part is known as slider and the stationary part is called stator. In LSM with coil, the major magnetic field is generated via the coil with electric current supplied to it which results in the translation of slider along the yoke and magnet due to the coil force [2]. Geometries with three dimensional are not tend to simple mathematical description in flux distribution hence it is difficult to precisely calculate the permeance for flux paths through the air region [7-8]. In this context, magnetic transient analysis in JMAG is used to perform the analysis and the MMF applied to a phase winding at any position can be expressed as in Equation (1).

$$F = F_g + F_s + F_r \quad (1)$$

Rewriting in terms of magnetic field density and flux path as in Equation (2).

$$F = T_{ph} i = \sum H_g l_g + \sum H_s l_s + \sum H_r l_r \quad (2)$$

where, F is referred to the total MMF per phase applied. F_g, F_s and F_r refers to the drop of MMF in the air gap, stator, coil and iron core respectively. H_g, H_s, H_r, and l_g, l_s, l_r are referred as the magnetic field intensity and flux path lengths of the air gap, stator, coil and iron core respectively.

3. RESEARCH METHODOLOGY

The research methodology consists of designed iron core LSM based on the coreless LSM and the optimized double layer coil iron core LSM. In this context, the phase winding of the coil is very crucial such the output coil force is of the same direction in order to increase the thrust force in the event of translation. On the other hand, the natural boundary of the model has to be set again due to different geometries of iron core LSM motor. The overall flow of the design project is as shown in Figure 3.

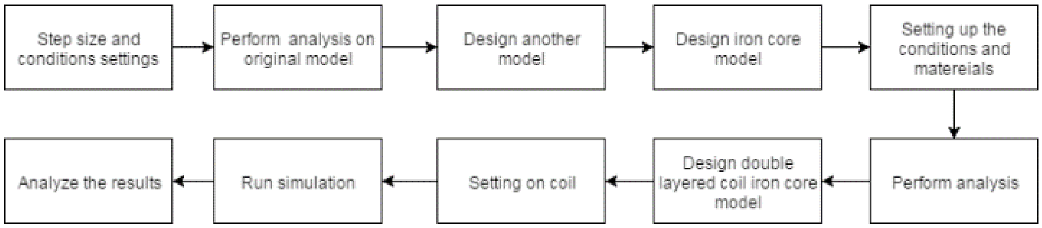

Figure 3: Flow of the design project

The step size and the conditions of the original coreless LSM is set before performing the thrust force-displacement analysis. In this particular design as shown in Figure 4, the total displacement of the coil from the initial point to the end of the point 84mm. By setting the step size of the study to 7, a constant displacement of 14mm per step can be obtained by diving the 84mm by 7. That being said, the slider translates 14mm per steps in the analysis. Once the analysis of the original model is successfully completed, the iron core model is designed as shown in Figure 5 and the optimized designed is proposed hereafter as shown in Figure 6.

Table 1 refers to the material used for all the parts in the iron core LSM model. Table 2 refers to the condition set for the simulation of magnetic transient analysis. In this context, since it is a LSM, hence the translation motion is set. Since the generation of magnetic flux is mainly via coil, hence Lorentz force is set. FEM coil for *u*, *v*, and *w* phase, the direction of the coil force is to be set as the same direction such that the coil force produced does not oppose each other in which results in the drops of thrust force. Element size of 1.2mm is defined for the meshing of the designed model in order to generate a more converge mesh such that the generated results can be more accurate. The design concept of a double layer coil iron core LSM can be further improved and optimized by adding a layer of magnet with yoke as supporting material as shown in Figure 7. Such design concept is to allow the flow of magnetic flux from the coil to the magnet to reduce the leakage of magnetic flux. That being said, the generation of thrust force can be increased tremendously due to the leakage of magnetic flux towards unnecessary direction is reduced.

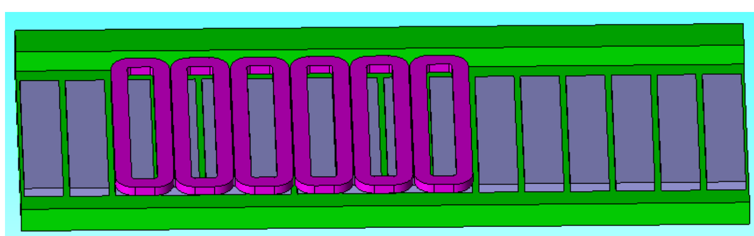

Figure 4: Coreless LSM

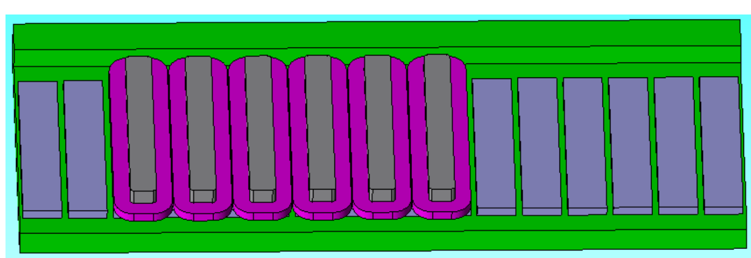

Figure 5: Iron core LSM

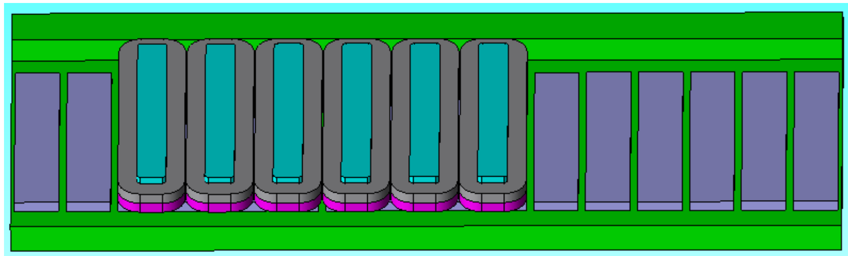

Figure 6: Double layer coil iron core LSM

Table 1
Material

Part	*Material*
Coil	Copper
Yoke	Custom sample material
Magnet	NEOMAX-44H (reversible)
Iron core	50JN1300

Table 2
Condition

No.	*Condition*
1.	Natural Boundary Iron Core
2.	Motion: Translation (Constant displacement) Rotor and Magnet
3.	Force: Lorentz Force Coil
4.	FEM Coil for U-Phase, V-Phase, W-Phase

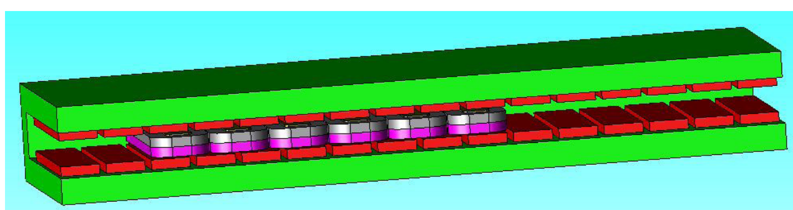

Figure 7: Optimized double layer coil iron core LSM

4. RESULTS AND DISCUSSIONS

In this section the design and analysis of the optimized double layer coil iron core LSM structure are discussed. 3D magnetic transient analysis is simulated. In this context, the generation of thrust force along the displacement is discussed. On the other hand, the average powers of the structures are compared. The main difference between an iron core LSM and a coreless LSM is in the thrust force generation. In this context, the generated thrust force of a conventional coreless LSM is generally lower than the iron core generated thrust force. This is why typical coreless LSM is suitable to be applied in area which requires extreme velocity control and positioning such as the automation machines in the assembly line of semiconductor industry. On the other hand, an iron core LSM is often used in lift system due to high starting thrust force in order to provide enough inertia to overcome the gravity and weight to lift up. In a coreless LSM, the thrust force variation is very low as the magnetic flux generated on the coil follows the trends to move to another coil through air gap. Such flow of magnetic flux will result in no cogging force produced in the coreless LSM. However, such situation does not happen in an iron core LSM as the magnetic flux generated on the coil will flow to another through the iron core. In this context, the variation of thrust force is high in an iron core LSM due the high starting thrust and the drops of thrust during the translation. In this context, the analysis is done on the single layer coil iron core LSM and it is noticed that the generated thrust force shown similar trend of high starting thrust and reduces afterwards. In order to further optimized the iron core LSM to produce an even higher thrust force. A double layer coil iron core LSM is proposed and results are simulated. It is noticed that there is a significant increase of thrust force when double layer coil is implemented as shown in Figure 8.

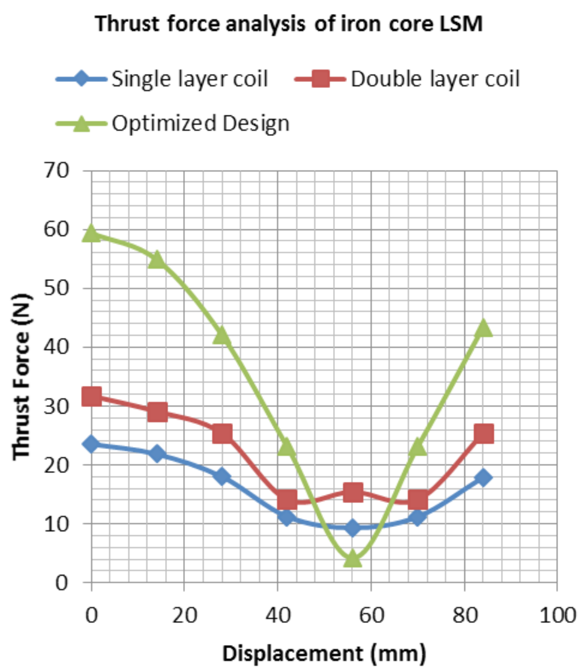

Figure 8: Comparison of thrust force with single layer coil, double layer coil iron core LSM and optimized design

On the other hand, it is noticed that the thrust force generated by the optimized designed is almost double of the double layer coil design. Such result proves that the optimized design concept is feasible to be implemented. Not only the thrust force generation but also the trend of curve of the thrust force along displacement where the optimized design yields a smooth 'sinusoidal-like' waveform which indicates the performance of the optimized design motor is very smooth and stable.

Where *F* is the force, *N* is the number of turns of coil windings and *I* is the current. Based on the Eq. (3), it is noticed that when either *N* or *I* increases, the force increases. However, an addition of a layer of coil will result in the higher average power due to the increase of current and such statement can be justified by the simulation where the average power of a single layer coil iron core LSM is only 15.18W whereas the power of double layer coil is 27W. However, the average power of the optimized design is only 28.36W and is only a slightly increase with the double layer coil iron core. The reason of the optimized design can produce almost double thrust force of the double coil design with minimum average power is due to the flow of magnetic flux from coil to the magnets on the top and bottom respectively. Such design prevents the leakage of magnetic flux and that being said the magnetic flux density is more concentrated in this context hence the generation of thrust force can be increased tremendously. Therefore, though there is a significant increase of thrust force when a double layer coil is implemented, the average power is also necessary to be taken into consideration as higher thrust requires higher power to be generated.

5. CONCLUSIONS

Based on the simulated results, it is concluded that the conventional iron core LSM is successfully optimized by implementing a double layer coil and magnet to it where it increases the starting thrust of the iron core LSM by nearly double without increasing much of the total average power. That being said, such design concept is feasible to be applied and implemented in industry where higher starting thrust is required. This design project can be further extended to study the windings of the double coil iron core LSM such that the analysis on the thrust force generation with different coil windings placement can be analyzed.

Acknowledgement

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