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Characteristic Analysis of a Permanent Magnet Transverse Flux Linear Motor with Spiral Core

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This paper presents a characteristic analysis method of a permanent magnet type transverse flux linear motor (TFLM) with spiral cores. The spiral cores are used as the mover cores in order to make 3-dimensional (3-D) magnetic flux paths at the TFLM which have 3-D magnetic flux flows. The 3-D Equivalent Magnetic Circuit Network Method is used to analyse the magnetic characteristics of the machine, and an imaginary part, 'flux barrier,' is introduced to consider the spiral core characteristic. Magnetic parameters such as flux, inductance, and thrust are calculated from the analysis results. The computed thrust forces are compared to measured values to confirm the accuracy of the analysis.

Keywords : equivalent magnetic circuit network (EMCN), flux barrier, spiral core, transverse flux machine

1. Introduction

In the factory automation system, there is a great demand for linear direct drives to avoid the drawbacks of traditional drives with rotary motors and mechanical motion conversion devices such as gearbox, belt, *etc.* Permanent Magnets (PMs) excited Transverse Flux Linear Motors (TFLMs) have been improved in transportation and high power systems. These kinds of motors promise far-reaching applications in the factory automation system and especially for linear direct drives.

PM excited TFLM has 3-dimensional (3-D) magnetic flux paths as shown in Fig. 1. While magnetizing directions of PMs are in the x-axis, the magnetic flux paths by winding currents are on the y-z plane. This characteristic makes it difficult to use a general laminated silicon steel core, which lamination direction is in one straight direction.

[1] and [2] show examples of making cores with general laminated silicon steel at a transverse flux machine (TFM). Teeth of the stator cores are bent not to interrupt 3-D magnetic flux flow. In the mover, however, soft magnetic composite (SMC) cores are used instead of laminated silicon steel cores. While it can make the 3-D magnetic flux path simpler than the laminated silicon steel core, the magnetic permeability of the SMC core is significantly lower than silicon steel and the material cost is high.

Therefore, in this paper 'spiral core' is used as a compromise between the general laminated silicon steel core and SMC core. Its material is silicon steel, and so the B-H characteristics are better than the SMC core. The silicon steel sheet is wound so that the lamination direction is in radial direction, and the wound shape is spiral as the core name, and it makes the 3-D magnetic flux path possible.

To analyze this object model, the 3-D Equivalent Magnetic Circuit Network (EMCN) method is used [3]. An imaginary part, 'flux barrier,' is introduced to consider the laminated core characteristics so that the objects are modeled as solid state in place of the laminated state in order to save analysis time. In terms of thrust force, the results for the cases with and without flux barriers are compared to each other and also compared to the measurement to show the effect of the analysis method.

2. Analysis Model

2.1. TFLM configuration

Fig. 1(a) shows a 3-D configuration of PM excited TFLM with spiral cores for one phase. The projected 2-D cross section is shown in Fig. 1(b) and the 3-D partial cross section is shown in Fig. 2. This type of TFLM has salient poles on both the stator and mover, and the ex-

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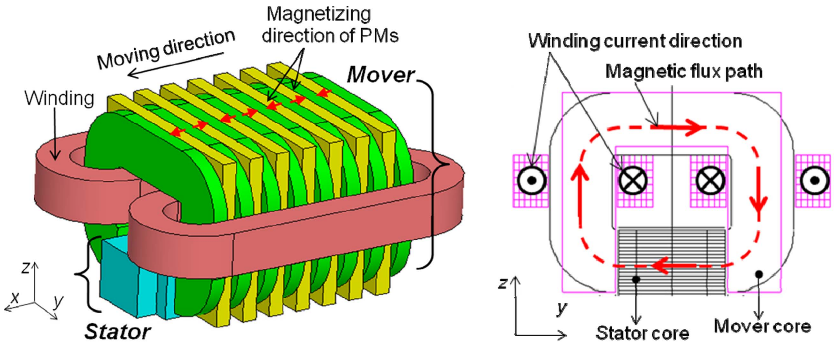


(a) 3D view of a TFLM (b) front view of a TFLM

Fig. 1. (Color online) Configuration of a TFLM with spiral cores.

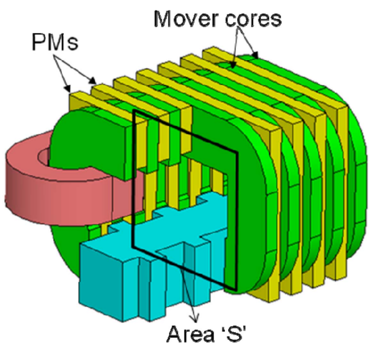


Fig. 2. (Color online) Partial cross section of a TFLM with spiral cores.

citation winding is carried on the mover. The principle of the operation is explained in [4].

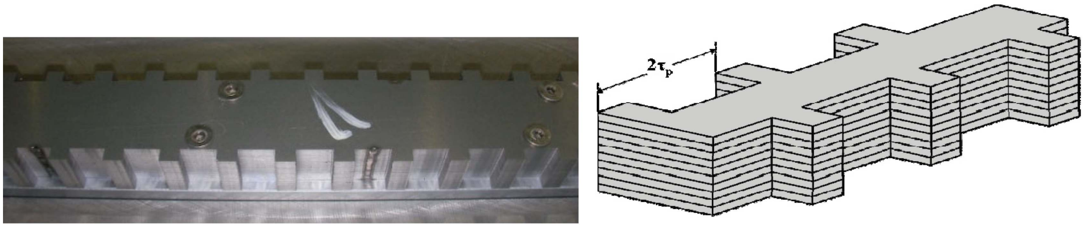
The mover has a structure in which each PM is interposed between two adjacent mover cores in order to form a high magnetic flux. In the mover cores, the magnetic flux path flows in the 3-D direction as shown in Fig. 1(a) and (b), so that spiral cores as shown in Fig. 3 are used. The exact shape of the 'spiral core' as the word means is shown in Fig. 3(a), where lamination direction is clearly seen, and it is the front view of y-z plane like Fig. 1(b). However, in order to use the spiral cores as mover cores, the spiral cores should be cut according to the size of the air-gap and the stator. Considering stator part (SP), spiral cutting cores are made as shown in Fig. 3(b) from Fig. 3(a), and PMs are attached on the front side of the cores as shown in Fig. 3(c). A module for a pair of mover poles consists of one spiral cutting core and 7 pieces of PMs, and one phase mover is made from the 12 modules. Stator poles are skewed for each opposite pole. The laminated direction of the stator core is shown in Fig. 4, and 2τp is the distance which is corresponding to one period of the source of electric power.

2.2 Analysis model considering spiral cores

While an analysis model should be described as practical shape to get exact results, lamination cores are usually modelled as solid cores to save analysis time. If magnetic flux only flows through the laminated cross section such as case-1 of Fig. 5(a), the analysis results are acceptable. However, if magnetic flux flows through two cores of which the lamination direction is across each other such as from core3 to core4 as shown in Fig. 5(b), the analysis results change. It is because that magnetic flux can flow through path 1 and path 2 in solid cores but it hardly flows through path 1 in lamination cores. The relative position of mover cores to stator cores in the

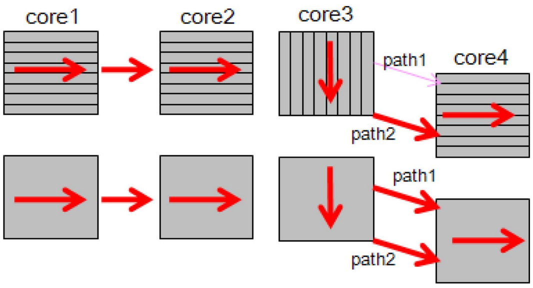
(a) spiral core (b) spiral cutting core (c) a module for mover

Fig. 3. (Color online) Mover core of a TFLM with spiral cores.



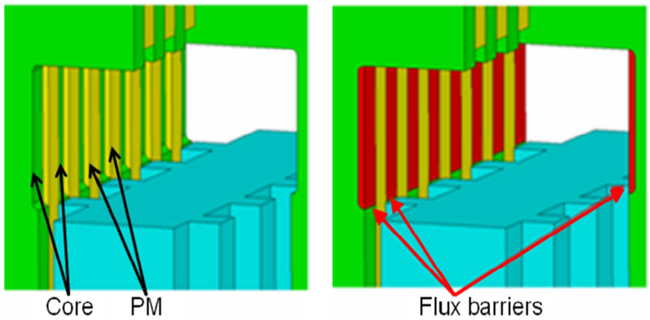
(a) partial picture of stator (b) stator core lamination

Fig. 4. (Color online) Stator core of a TFLM with spiral cores.



(a) case-1 (b) case-2

Fig. 5. (Color online) Concept of magnetic flux flow through solid and lamination cores: (up) lamination cores, (down) solid cores.



(a) model without flux barrier (b) model with flux barrier

Fig. 6. (Color online) Conceptual configurations of analysis models according to flux barrier existence.

TFLM with spiral cores is the same state as Fig. 5(b).

In the case of TFLM with spiral cores, if magnetic cores are modelled by solid cores only, it increases the error of analysis. The values of the analysis results can be relatively higher than practical values because magnetic flux can flow through any direction of the cores with the same permeability in analysis although, in fact, the permeability is quite different between the perpendicular and parallel direction to lamination. Therefore, flux barriers are added to the analysis model with solid cores to consider the permeability difference.

Table 1. Force variation depending on thickness of flux barrier.

Thickness (mm)	0	0.5	1.0	1.5	*2.0*
Thrust force (N)	997	844.3	843.8	843.2	*842.4*

Fig. 6 shows conceptual configurations of analysis models according to flux barrier existence. When the window of ‘area S’ in Fig. 2 is zoomed in, the result of the practical model looks like Fig. 6(a). When the flux barriers are

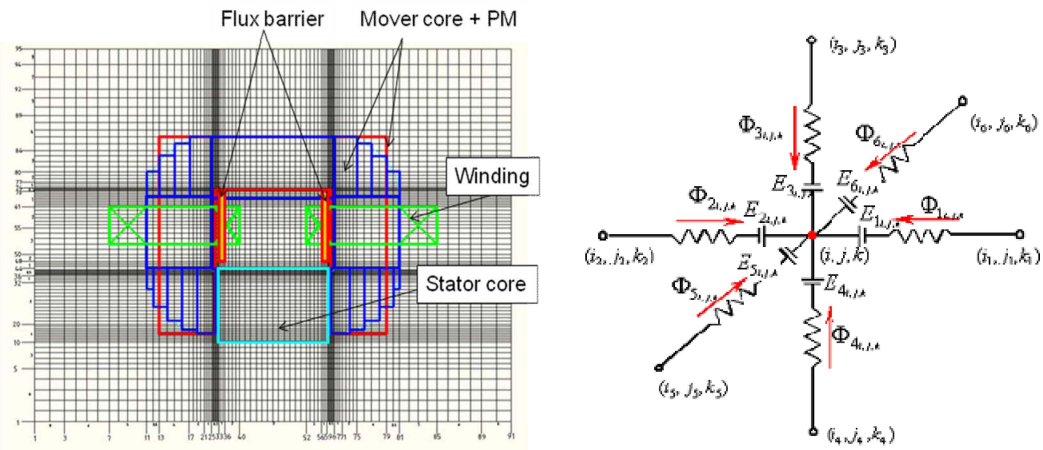


Fig. 7. (Color online) Meshed model for 3D EMCN analysis (left) and the circuit of one element and its adjacent elements (right).

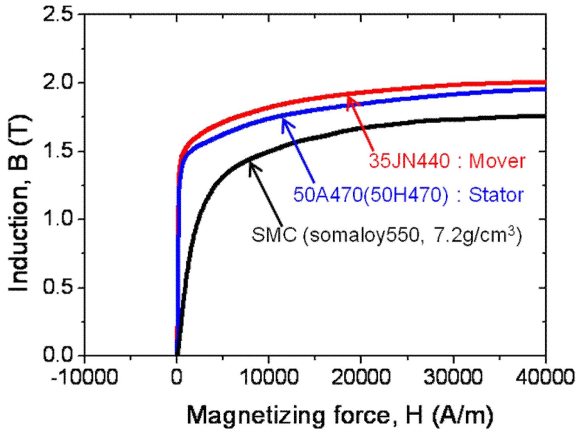


Fig. 8. (Color online) Magnetic material characteristics (B-H curves).

considered for the spiral cores of the mover, the magnetic flux barriers are modelled on the inside of mover cores to consider lower permeability as shown in Fig. 6(b). Also, it is modelled with low relative permeability of 0.01 (the smallest value for used software) to prevent magnetic flux from flowing in an undesired direction. The thickness of the flux barrier is decided by saturation force value, 2 mm as listed in Table 1.

Fig. 7 shows a meshed analysis model for magnetic analysis by using 3-D EMCN. It is the front view of the y-z plane like Fig. 1(b). The round corner is expressed by stepped rectangular because of hexahedral elements. The circuit of one element and its adjacent elements are also shown in Fig. 7. The circuit is corresponding to the electric circuit composed of voltage, current, and resistance so that 3-D EMCN uses scalar potential as a field variable. The detailed explanation is in [3].

Fig. 8 shows the comparison of magnetic material characteristics. It is B-H curves by direct current source.

Table 2. Specifications of a TFLM with spiral core.

Contents	Values
Stator core material	50A470
Mover core material	35JN440
PM material	NdFeB-sintered (N40H)
No. of pole/phase, phase	Pole=12, phase=3
No. of turns/phase	42
Rated magneto-motive force	4000 (AT)

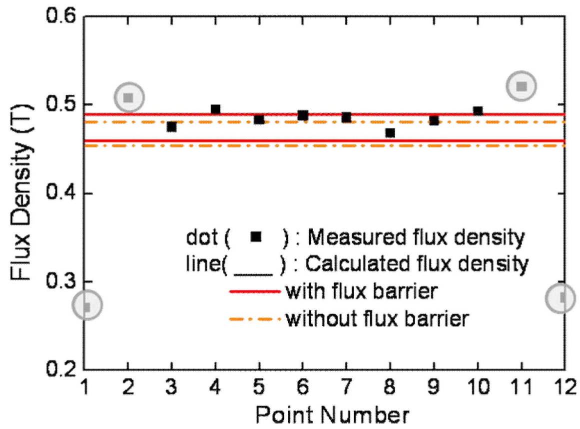


Fig. 9. (Color online) Flux density of mover core inside.

The spiral core is made by silicon steel 35JN440 winding so that the characteristic is better than SMC core's. The brief specification for analysis is listed in Table 2.

3. Analysis and Measurement Results

Before calculating motor characteristics, magnetic material characteristic is confirmed first. Fig. 9 presents the comparison of measured and calculated flux densities on the surface of the mover core inside. When the characteristics

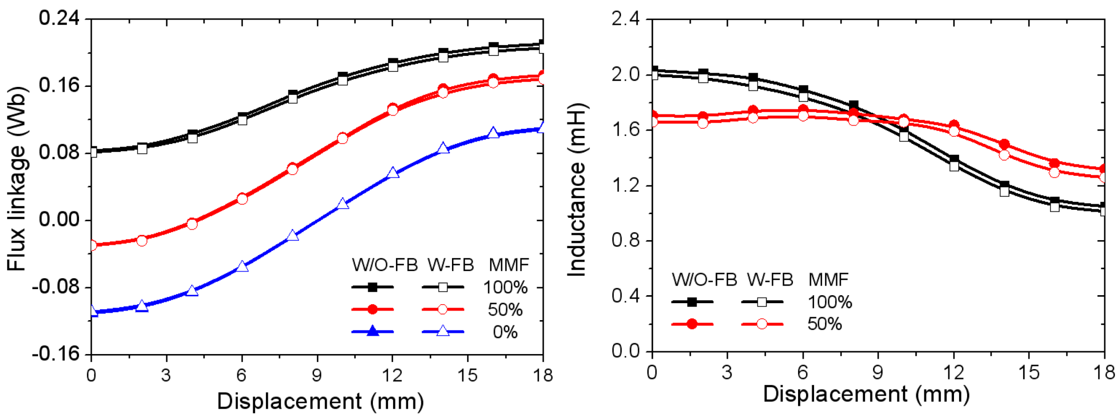


Fig. 10. (Color online) Parameters according to mover displacement and MMF variation (W/O-FB: analysis model without flux barrier, W-FB: analysis model with flux barrier).

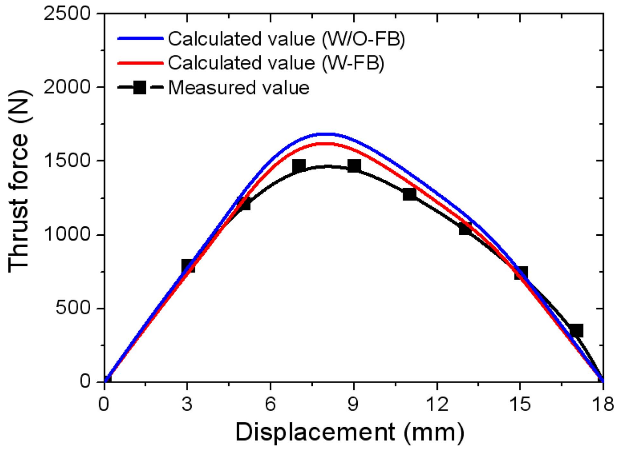


Fig. 11. (Color online) Thrust force per phase (W/O-FB: analysis model without flux barrier, W-FB: analysis model with flux barrier).

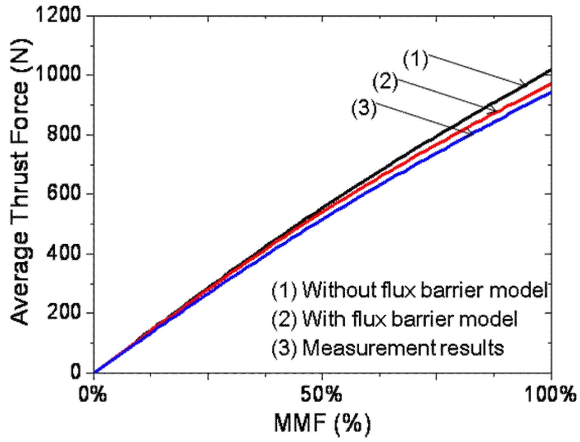


Fig. 12. (Color online) Average thrust force according to MMF variation.

of magnetic materials (PMs and mover cores) are considered as Table 2, the flux density calculation results are very similar to the measured ones. Furthermore, the analysis results from the model with flux barriers have fewer errors compared to the results from the model without flux barriers.

When the calculated motor characteristics are compared with measured ones, results according to the analysis model with and without flux barriers are also compared below. Input current is considered as a constant value depending on mover displacement.

Fig. 10(a) shows the flux linkage of one phase coil according to mover displacement and magneto-motive force (MMF). The rated MMF is 4000 ampere-turns (AT), and it is expressed as 100% MMF. When the MMF value is low, the analysis results depending on flux barrier existence are not quite different. At rated MMF, the flux linkage of the analysis model without flux barriers is a little higher than the value of the analysis model with flux barriers. The little difference means that the analysis model is not magnetically saturated until rated MMF. When MMF is beyond the threshold causing magnetic saturation, the leakage and overhang flux will be increased, so that more flux linkage is calculated if there is no flux barrier.

Fig. 10(b) shows phase inductance according to displacement and MMF. Here, the inductance is incremental inductance which is calculated by the equation, flux variation divided by current variation. Calculated inductance for 50% MMF means that both flux and current variations are between values of 0% and 50% MMF. The flux linkage of the analysis model without flux barriers is high, so that the inductance of the analysis model without flux barriers is higher than the values of the analysis model with flux barriers.

Fig. 11 and Fig. 12 show the thrust force per phase and average thrust force, respectively. The calculated results have differences between analysis models with and without flux barriers, and there are also differences between calculated and measured results. The differences become bigger when the mover cores are unaligned with stator cores (between 6 and 12 mm). In this position, the leakage and overhang flux is remarkably increased compared to the flux in the aligned position. It is not because of saturation, but rather because of an enlarged air-gap causing bigger magnetic resistance. Even though the flux barrier model is used to compensate the magnetic re-

Table 3. Comparison of calculated and measured results.

Contents			Values	Error (%)
emf at 1 m/s	Calculated value (V)	Without flux barrier	13.6	0.7
		With flux barrier	13.5	1.5
	Measured value (V)	-	13.7	-
Thrust force at 100%MMF	Calculated value (N)	Without flux barrier	1023	*8.3*
		With flux barrier	978.7	*3.6*
	Measured value (N)	-	944.3	-

sistance, there is still a difference between calculated and measured ones, but the difference is reduced. Table 3 shows the improved results.

4. Conclusions

This paper dealt with PM excited TFLM with spiral core in the mover. The magnetic characteristics of the analysis model were analyzed based on the 3-D EMCN method. The flux barrier was introduced to prevent flux flow in an undesired direction considering lamination direction. The measurement results confirmed the accuracy of the simulation with less than 4% difference in average thrust force.

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