Optimal Design of a Permanent Magnet Linear Synchronous Motor With Low Cogging Force

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Abstract —In this paper, a technique for minimization design of the cogging force in slotted permanent magnet linear synchronous motors (PMLSMs) is presented. A two-step minimization process depending on the slotting and end effects is proposed. The Taguchi's parameter method coupled with 2-D and 3-D finite element analysis (FEA) is employed to minimize the cogging force.

I. Introduction

The cogging force generated in slotted PMLSMs is caused by the slotting and end effects. Several techniques have been proposed to reduce cogging force by many researchers including the proper pole and slot combination selecting, the magnet length adjustment, the magnets or slots skewing, semi-closed slot designing, the suitable armature length selecting, the proper armature outlet edge shape designing, the proper tooth edge chamfering, auxiliary poles (APs) utilizing [1]-[5], and control strategies.

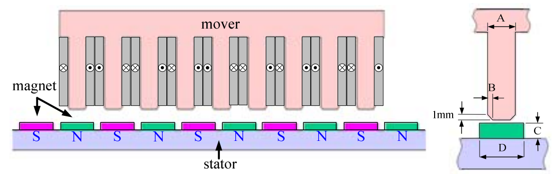
This paper is concerned only the design aspect to minimize the cogging force in slot and end regions. A two-step minimization process depending on the slot or end region is performed. In the first step, technique for optimal design of slot region is considered, and the Taguchi's parameter method coupled with 2-D FEA is conducted, while in the second step, regions in both slots and two ends which are equipped with APs and aluminum alloys (ALs) are considered, and the Taguchi's parameter method coupled with 3-D FEA is employed to minimize the cogging force [6].

II. Model of Motor

Fig. 1 shows the initial design of a single-sided, 8P/9S PMLSM. The machine has an average thrust force (F_{avg}) of 148.65 Nm and a peak-to-peak value of cogging force (F_{cog}) is 57.5 N. It is seen that F_{cog} / F_{avg} is about 38.68%.

III. First-Step Optimization

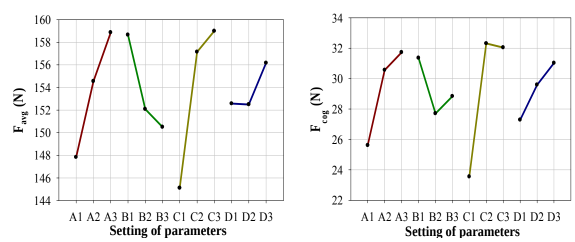
Fig. 1(b) and Table I show the selected four factors A, B, C, and D affecting the cogging force due to slotting effect. A is the width of tooth in mm, B is the width of chamfered tooth edge in mm, C is the height of magnet in mm, and D is the width of magnet in mm. Each factor has three levels, the performance of the machine in the orthogonal array (OA) L_9 matrix experiments can be calculated using 2-D FEA as shown in Table I. The influence of each factor on the F_{avg} and the F_{cog} are shown in Fig. 2. It is noted that there is no element selected to constitute the elements of the optimum design for minimum F_{cog} and maximum F_{avg} from Fig. 2. Therefore, before selecting optimal setting of parameters for robust design, it is necessary to determine the relative importance of various factors on machine performance by conducting analysis of variance (ANOV). These results are listed in Table II. It is seen that from Fig. 2 and Table II, the best combination of design parameters is determined to be (A3, B3, C1, D1).



(a) (b)
Fig. 1. Initial design of motor. (a) Front view. (b) Chamfered tooth.

TABLE I
L-9 OA AND MACHINE PERFORMANCE

Experiment	A	B	C	D	F_{avg} [N]	F_{cog} [N]
1	5.5	0.5	2.75	12	126.98	29.721
2	5.5	1	3.25	12.5	131.77	40.782
3	5.5	1.5	3.75	13	135.26	44.230
4	6	0.5	3.25	13	146.83	55.773
5	6	1	3.75	12	139.44	44.343
6	6	1.5	2.75	12.5	125.63	36.783
7	6.5	0.5	3.75	12.5	149.04	54.967
8	6.5	1	2.75	13	134.14	38.973
9	6.5	1.5	3.25	12	140.22	48.170



(a) (b)
Fig. 2. Main factor effects on (a) thrust force and (b) cogging force.

TABLE II
EFFECTS OF FACTORS ON MOTOR PERFORMANCE INDEXES

	F_{cog}		F_{ave}	
	SSF	Factor effects	SSF	Factor effects
A	140.892	24.83%	146.21	27.87%
B	46.753	8.24%	88.476	16.87%
C	332.282	58.56%	269.006	51.28%
D	47.542	8.37%	20.867	3.98%
Sum	567.470	100%	524.559	100%

IV. SECOND-STEP OPTIMIZATION

To minimize the component of cogging force caused by the end effect, two APs are fixed on both sides of the mover as shown in Fig. 3 [5]. The AP contains an iron tooth and an AL is connected between the mover and the AP. Both of two APs and the magnets are skewed in the opposite directions in Fig. 3(b). The width of one side of an AP is designed to be equal to 1/4 pole pitch (τ_p)

As before, four factors, A, B, C and D corresponding to four design variables are chosen as shown in Fig. 3, and each at three levels. To reduce the number of independent variables, the geometric parameters A, B, and D are normalized by dividing all dimensions by the pole pitch (τ_p). Where A is the magnet skew length (levels 0, 0.25 and 0.5), B is width of an AL (levels 1, 0.5, and 0.25), C is the distance between the bottom of an AP and the bottom of the slot tooth in mm (levels 0, 3 and 6), and D is the width of an AP which skews the AP (levels 1, 0.25, and 0.5). Results for each experiment are shown in Table III. Fig. 4 shows the influence of each factor on F_{avg} and F_{cog}. Table IV summarizes the results of ANOV. It is noted in Fig. 4 and Table IV that the best combination of design parameters is determined to be (A1, B2, C2, D3). Table V compares the data of the machine between the initial, the first-step optimized, the second-step optimized designs and measurement. It can be seen that the cogging force reduces from the initial design of 57.5 N to the second-step optimized design of 17.97 N. It is seen that reduction of cogging force results in a small reduction of thrust force.

V. CONCLUSION

This paper has applied the two-step optimization using the Taguchi parameter method coupled with 2-D and 3-D FEA to design optimization for the minimization the cogging force and maximization of the average thrust force of a PMLSM. It has been shown that the technique presented in this paper is effective for obtaining the design parameters having low levels of cogging force for PMLSMs.

ACKNOWLEDGMENT

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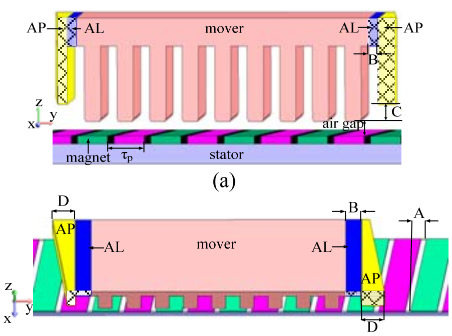
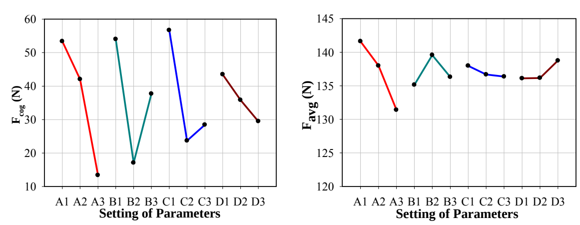


Fig. 3. PMLSM topology showing geometrical definitions, (a) Front view. (b) Top view.

TABLE III
L-9 OA AND MACHINE PERFORMANCE

Experiment	A	B	C	D	F_{avg} (N)	F_{cog} (N)
1	0	1	0	1	139.82	98.74
2	0	0.25	3	0.25	143.01	21.17
3	0	0.5	6	0.5	142.02	40.18
4	0.25	1	3	0.5	137.53	40.41
5	0.25	0.25	6	1	139.01	22.24
6	0.25	0.5	0	0.25	137.41	63.45
7	0.5	1	6	0.25	128.05	22.89
8	0.5	0.25	0	0.5	136.69	7.85
9	0.5	0.5	3	1	129.48	9.46



(a) (b)

Fig.4. Main factor effects on (a) average thrust force and (b) cogging force.

TABLE IV
EFFECTS OF VARIOUS FACTORS ON MOTOR PERFORMANCE

	F_{cog}		F_{ave}	
	SSF	Factor effects	SSF	Factor effects
A	2545.31	37.40%	160.71	76.35%
B	2054.58	30.19%	31.68	15.05%
C	1909.31	28.06%	4.39	2.08%
D	294.83	4.35%	13.69	6.52%
Sum	6804.03	100%	210.47	100%

TABLE V
COMPARISON RESULTS

	Initial	1^{st}-step	2^{nd}-step	Measurement
F_{cog} [N]	57.5	37.0	17.97	16.50
F_{avg} [N]	148.65	134.44	142.96	141.60
F_{cog} / F_{avg} [%]	38.68	27.52	12.57	11.65