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Cogging Force Minimization of a Tubular Flux-Switching Permanent Magnet Motor Using Un-equal Width Stator Slots Based on Taguchi Method

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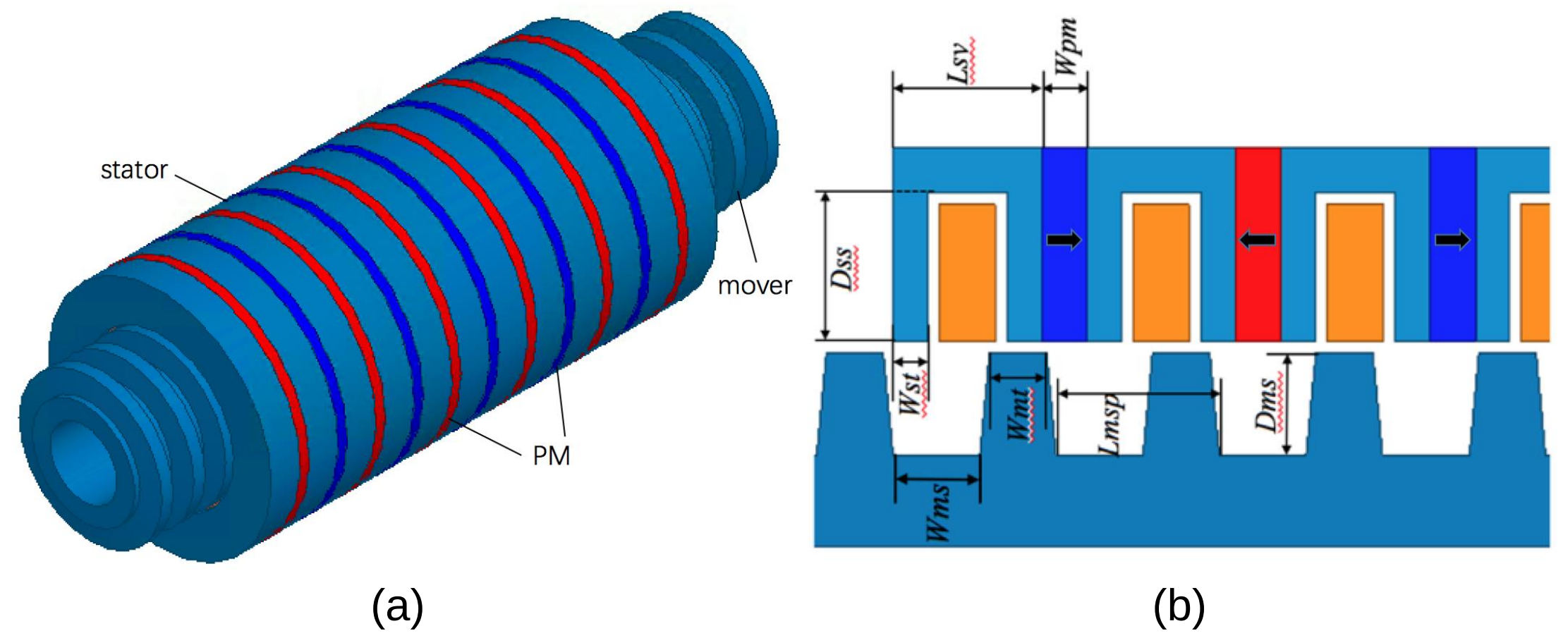
➢1. INTRODUCTION

- The cogging force caused by the cogging effect and end effect will seriously affect the operation of a tubular flux-switching permanent magnet motor (TFSPMM). This paper proposes a method to weaken the end effect and minimize the cogging force and force ripple of a TFSPMM using un-equal width stator slots. The proposed method can significantly decrease the cogging force and force ripple and keep the electromagnetic force basically unchanged. The pm flux linkage, cogging force and electromagnetic force are calculated by the two dimensional (2D) finite element method (FEM).
- To overcome the problem of excessive calculation, the Taguchi method is performed to find the optimal combination of stators with unequal slot width.

➢2. TOPOLOGY OF TFSPMM AND MAIN PARAMETERS

Fig.1 shows the main topology and main design parameters of TFSPMM. The permanent magnets (PMs) in TFSPMM are located on the short primary stator side and they are magnetized along the axial direction. Adjacent PMs are magnetized along the opposite directions, and all the PMs are sandwiched between the U-shaped stator cores. The used winding is the global ring winding and it is located on the inner space of U shaped stator cores. In TFSPMM, there is no winding or PM on the long mover side, thus the material cost can be kept very low and the mechanical robustness can be guaranteed. The model shown in Fig.1(b) is built around Z-axis, which can be considered as rotational symmetry around the Z-axis. The method reduces modeling and computation time.



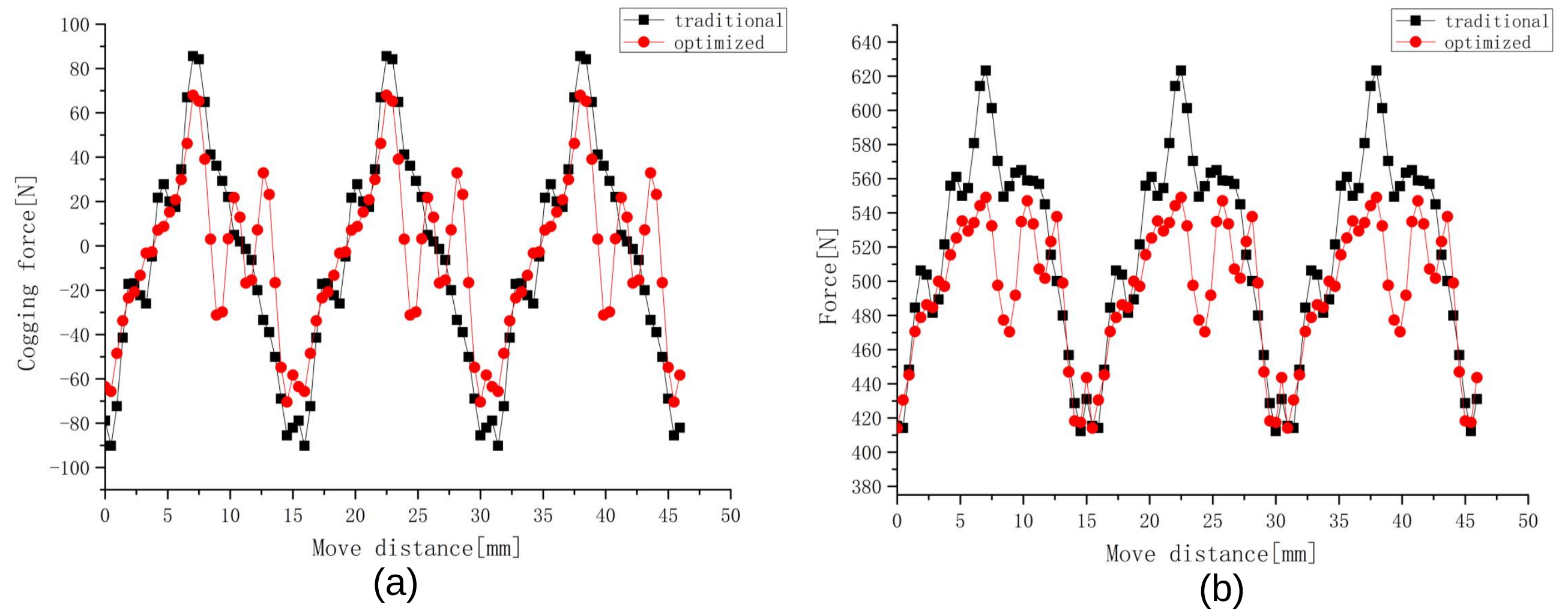
(a) (b)

Fig. 1. Main topology and parameters of the TFSPMM.

Table Ⅰ Main Dimensions of Proposed FSPMTM

Parameters	Symbol	Value	Unit
Stator inner radius	R_{si}	33	mm
Stator outer radius	R_{so}	50	mm
Stator yoke length	L_{sy}	13	mm
Stator slot depth	D_{ss}	7	mm
Stator tooth width	W_{st}	3	mm
PM width	W_{pm}	4	mm
Effective axial length	L_{ea}	200	mm
Air gap length	L_{ag}	1	mm
Shaft radius	R_{shaft}	15	mm
Mover outer radius	R_{mo}	32	mm
Mover slot depth	D_{ms}	9	mm
Mover slot width	W_{ms}	200/14-6.68	mm
Mover teeth width	W_{mt}	5	mm
Mover slot pitch length	L_{msp}	200/14	mm

➢3. Cogging Torque Minimization of TFSPMM by Un-Equal Width Stator Slots Based on Taguchi Method



(a) (b)

Fig. 2. (a) Cogging force of the FSPMTM, (b) force of the TFSPMM.

In the early calculations, three stators at the ends were selected as optimization objects to observe the performance change of the motor by changing their slot width. The width of each slot varies from 12 to 14, with a step size of 1. This produces a total of 27 different combinations, a number that the software can also calculate, and provides a good result shown in Fig. 2.

However, when the number of parameter changes increases, as shown in Table II, the number of parameter changes is 5, which produces a total 125(5*5*5) different combinations. which will take a very large amount of computer resources and a very long time to complete the calculation by using software.

Table II Optimization Variables and Value Levels of TFSPMM

factor	Slot1/mm	Slot2/mm	Slot3/mm
Level 1	12	12	12
Level 2	12.5	12.5	12.5
Level 3	13	13	13
Level 4	13.5	13.5	13.5
Level 5	14	14	14

By using the Taguchi method, only 25(5*5) different combinations need to be calculated, which saves computer resources, reduces computing time and improves computing efficiency The orthogonal table shown in Table III, includes 25 different levels of combinations and their corresponding electromagnetic performances.

Table III Experiment Matrix and FE Result

No	Control factors			Ψ_A/mWb	Ψ_{PP}/mWb	F_{PP}/N
	Slot1	Slot2	Slot3			
1	1	1	1	-1.4	2.8	146
2	1	2	2	-1.4	2.9	208
3	1	3	3	-1.3	3	246
4	1	4	4	-1.2	3	254
5	1	5	5	-1.1	2.9	252
6	2	1	2	-1.1	2.8	96
7	2	2	3	-1	2.9	182
8	2	3	4	-0.9	3	249
9	2	4	5	-0.8	2.9	296
10	2	5	1	-2.2	2.9	114
11	3	1	3	-0.6	2.8	67
12	3	2	4	-0.5	2.9	173
13	3	3	5	-0.4	2.9	273
14	3	4	1	-1.8	2.9	149
15	3	5	2	-1.8	2.9	87
16	4	1	4	-0.2	2.8	90
17	4	2	5	0	2.8	183
18	4	3	1	-1.4	2.8	143
19	4	4	2	-1.4	2.9	115
20	4	5	3	-1.4	2.9	82
21	5	1	5	0.4	2.7	134
22	5	2	1	-1	2.7	86
23	5	3	2	-1	2.8	89
24	5	4	3	-1	2.9	80
25	5	5	4	-0.9	2.8	76

$$m=\frac{1}{n}\sum_{i=1}^{n} m_i \quad (1)$$

Table IV Average Values of Experiments

Parameters	Ψ_A/mWb	Ψ_{PP}/Wb	F_{PP}/N
Average	-1.016	2.864	158

where m is the average value of all experimental results of one parameter in Table III, n the number of experiments, m_i the value of experimental result of one parameter in its ith experiment.

$$m_{y_A}(slot_1)=\frac{1}{5}(y_{A1}+y_{A2}+y_{A3}+y_{A4}+y_{A5}) \quad (2)$$

Table V Average Values of Performance Indexes for Parameters at Each Level

Parameters	Level	Ψ_A/mWb	Ψ_{PP}/mWb	F_{PP}/N
Slot1	1	-1.28	2.92	221
	2	-1.2	2.9	187
	3	-1.02	2.88	150
	4	-0.88	2.84	123
	5	-0.7	2.78	93
Slot2	1	-0.58	2.78	107
	2	-0.78	2.84	166
	3	-1	2.9	200
	4	-1.24	2.92	179
	5	-1.48	2.88	122
Slot3	1	-1.56	2.82	128
	2	-1.34	2.86	119
	3	-1.06	2.9	131
	4	-0.74	2.9	168
	5	-0.38	2.84	228

Ψ_{A1}~ Ψ_{A5} respectively represents the average values of Ψ_A of 5 experiments when the level of stator slot1 is 1.

$$s^2=\frac{1}{5}\sum_{i=1}^{5}\left[m_n\left(S_i\right)-m\left(S\right)\right]^2 \quad (3)$$

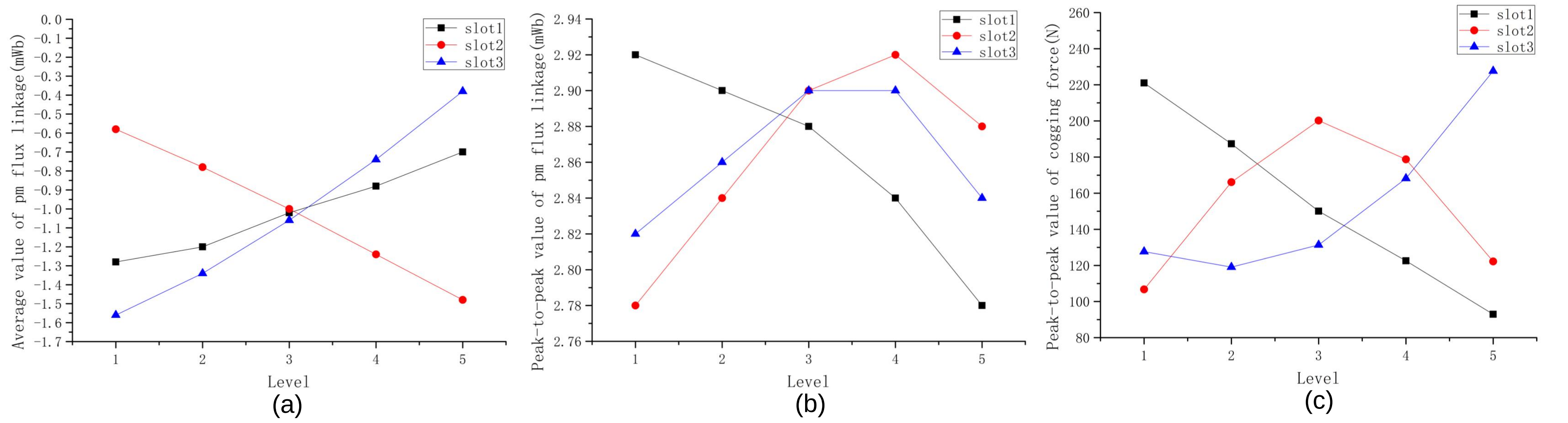
Table VI Variance And Ratio of Performance Indexes for Parameters at 5 Levels

Parameters	Ψ_A/Wb		Ψ_{PP}/Wb		F_{PP}/N	
	σ^2x10^8	ratio	σ^2x10^9	ratio	σ^2	ratio
Slot1	4.44	13.7%	2.46	41.4%	2067	42.1%
Slot2	10.23	31.6%	2.46	41.4%	1227	25%
Slot3	17.67	54.6%	1.02	17.2%	1610	32.8%

where σ^2 is the variance, N the number of level(5 in this paper), X the variable($m_n(S_i)$in this paper), μ the population average($m(S)$in this paper).

According to Taguchi method, Table IV, V and VI are calculated from formulas (1), (2) and (3). In order to observe the effect of data changes on electromagnetic properties more directly, the data in Table V is made into the broken line diagram as shown in Fig. 3.

As can be seen from Fig .3 (a), with the increase of the width of stator slot1 and slot3, the average value of pm flux linkage decreases gradually. On the contrary, the average value of the pm flux linkage increases gradually with the increase of the width of stator slot2. For the peak-to-peak value of pm flux linkage shown in Fig. 3 (b), the parameter changes have little influence on it. As for the peak-to-peak value of cogging force shown in Fig. 3(c), it decreases with the increase of width of stator slot1, and when the increase of slot2 and slot3 width, it shows the maximum and minimum value respectively.



(a) (b) (c)

Fig. 3. The electromagnetic performance of each parameter at different levels, (a) the average value of the pm flux linkage at different levels of each parameter, (b) the peak-to-peak value of the pm flux linkage at different levels of each parameter, (c) the peak-to-peak value of the cogging force at different levels of each parameter.

Fig. 4 shows the comparison of A phase PM flux linkage between the initial design and the second optimized design. Fig. 5 and Fig. 6 show the cogging force and thrust force comparison among the initial design and two optimized designs.

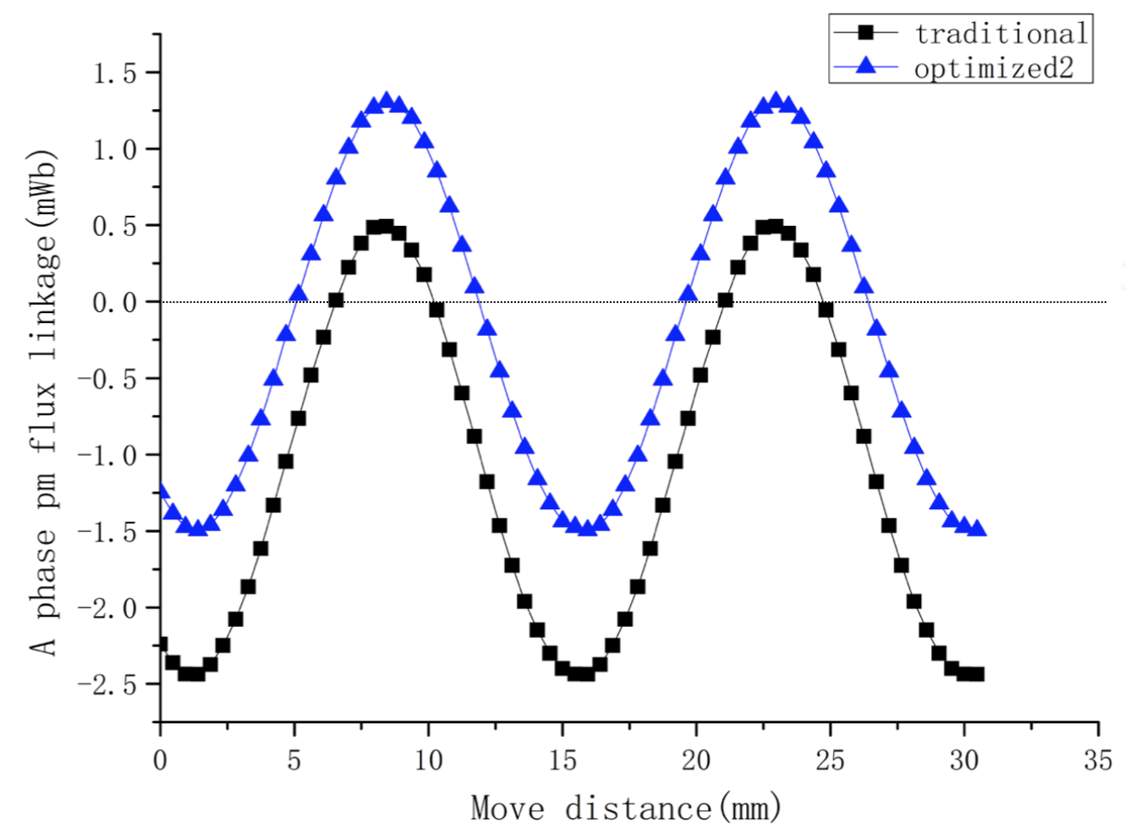


Fig. 4. Thrust force of the traditional TFSPMM and optimized TFSPMM.

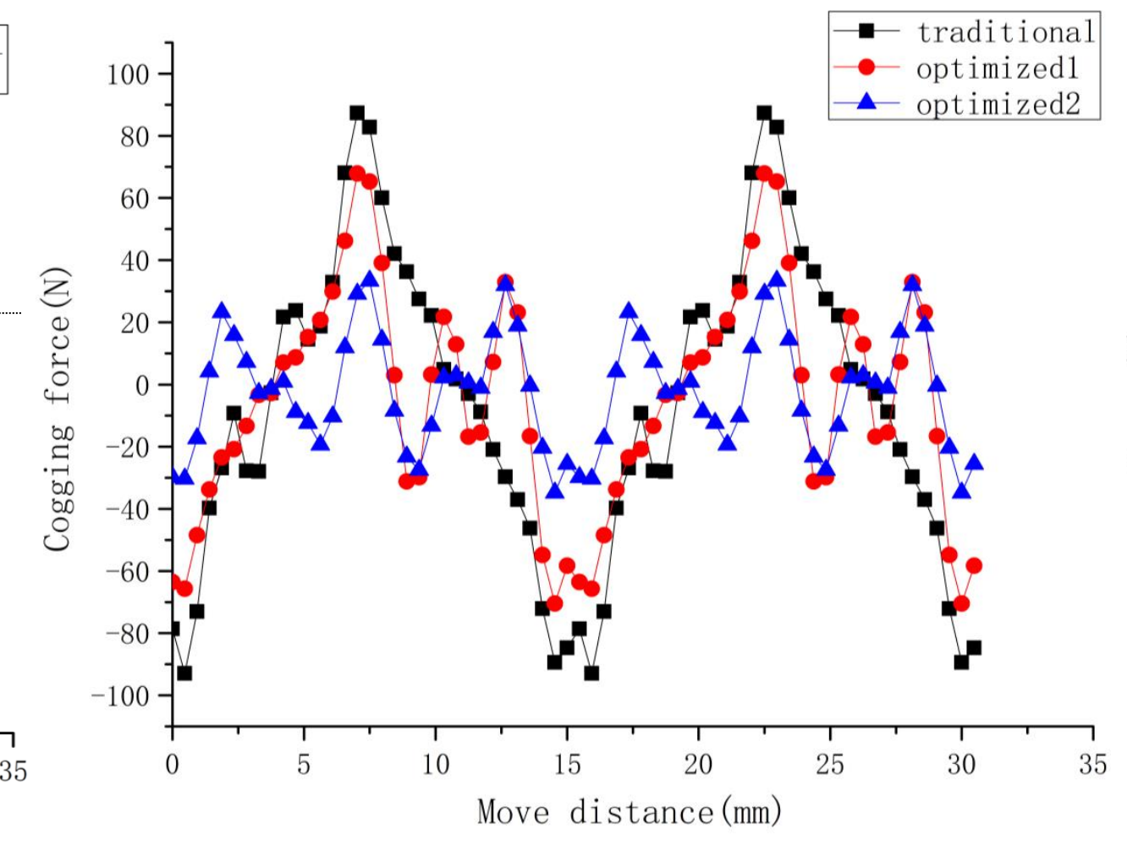


Fig. 5. Cogging force of the traditional TFSPMM and optimized TFSPMM.

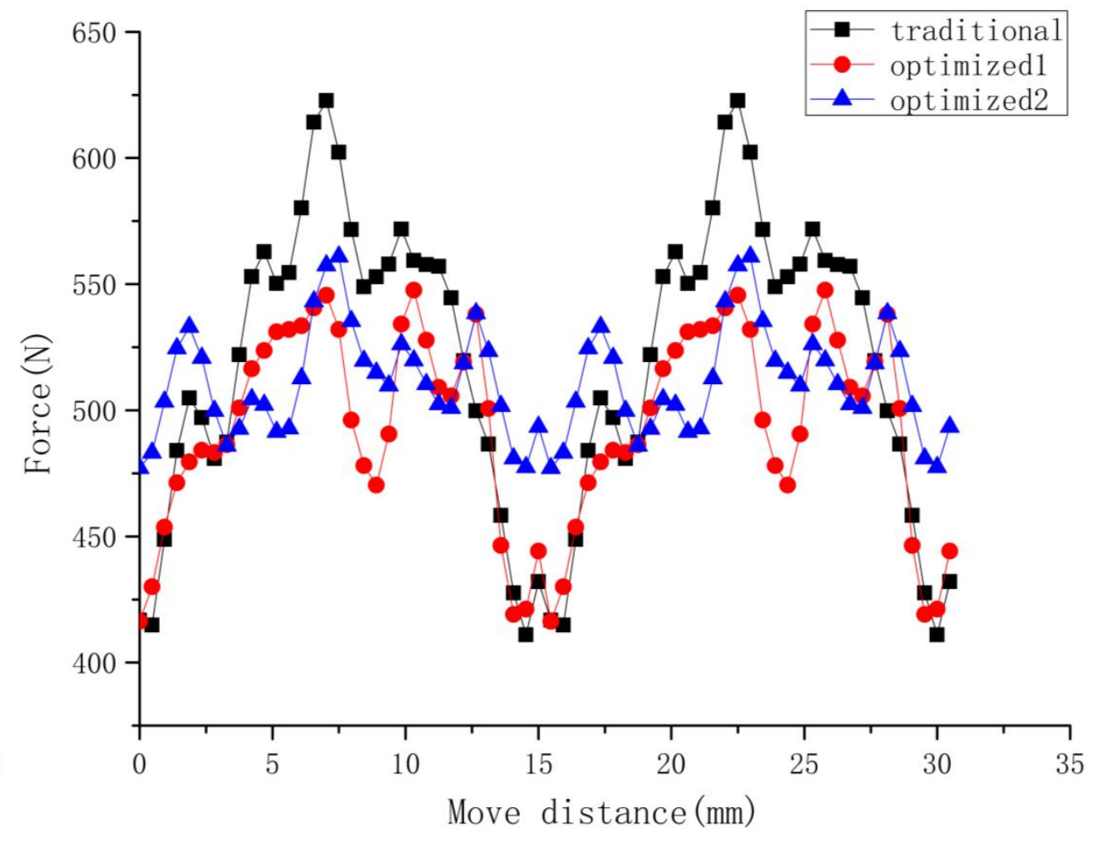


Fig. 6. Thrust force of the traditional TFSPMM and optimized TFSPMM.

➢4. CONCLUSIONS

(1)In this paper, the structure of un-equal width stator slots is proposed, in order to reduce the impact of the end effect. On the premise of not changing the volume of machine, the end effect is weakened. Moreover, the cogging force and force ripple caused by end effect is reduced by using the un-equal width stator slots to adjust the symmetry of the PM flux linkage.

(2)Taguchi design method was adopted to optimize three stator parameters at the end of the TFSPMM, aiming at the minimum average value of PM flux linkage, maximum peak-to-peak value of PM flux linkage and minimum cogging force, and it is effective in optimization design.