Application for Optimization of New Soft Magnetic Material Motor by Taguchi Method

Yixuan Song, Xusheng Wu, and Wei Gao

***Abstract*—The application of new soft magnetic materials in permanent magnet motor can effectively reduce the loss of motor and improve the efficiency of motor. Taguchi method is a local multivariable and multi-objective optimization method widely used in various engineering problems, which can effectively improve the efficiency of engineering optimization. In this paper, based on a 25kW, 1700r/min three-phase permanent magnet motor, the relevant motor model is established in the finite element simulation software, and the relevant simulation analysis is carried out. Combined with Taguchi method optimization, the local optimal structure scheme is obtained. Through optimization, the motor can maintain high efficiency, reduce the cogging torque of the motor by 53.45%, reduce the torque ripple by 36.79%, and increase the torque generated by the permanent magnet per unit mass by 21.42%. Through this optimization, the overall performance of the motor has been significantly improved. The research content of this paper verifies the feasibility of the application of Taguchi method in the optimization of new soft magnetic material motor, provides a new idea for the optimization design of new soft magnetic material motor, and also provides a certain reference for the local multi-objective optimization of the electromagnetic structure of other similar motors.**

***Index Terms*—Motor optimization, Taguchi method, New soft magnetic, Multi-objective optimization, High torque motor.**

I. Introduction

COMPARED with induction motor, permanent magnet synchronous motor has many advantages, such as higher power factor, high efficiency, small volume, higher torque density, constant speed and light weight. In recent years, due to the further improvement of the high temperature resistance of NdFeB and other permanent magnet materials and the decline of the price of related products, permanent magnet motors are more widely used in national defense, industry, agriculture and daily life. At present, permanent magnet motors are developing towards high power and high performance, and the varieties and application fields of permanent magnet motors are becoming more and more extensive [1],[2]. The application of new soft magnetic materials has further improved the performance and efficiency of the motor. On the basis of improving the efficiency, reducing the cogging torque and torque fluctuation of permanent magnet motor has become a new problem.

The application of amorphous soft magnetic material rose in the late 1970s. It is a new type of soft magnetic material, the amorphous atoms are arranged in short-range order and long-range disorder, which greatly reduces the anisotropy of the material and is conducive to obtaining high permeability and low coercivity in structure [3]. Among the commonly used amorphous alloy soft magnetic materials at present, the iron-based amorphous alloy permeability, excitation current and iron loss are better than those of traditional silicon steel, and the energy-saving effect is remarkable [3]. Sun Zhe and Liu Mingji from North China Electric Power University studied and designed a Halbach array magnetic pole to optimize and design a 36000r/min, 12kW 4-pole surface mounted amorphous alloy high-speed permanent magnet synchronous motor, The maximum tooth temperature of the optimized motor is reduced from 110℃ to 96℃ [4], [5], Chris Jensen of Fermi National Accelerator Laboratory (Fermilab) and Thomas Lipper of the University of Wisconsin Madison did relevant research on amorphous alloy permanent magnet brushless DC motor in the early stage, and proposed a shaft field permanent magnet brushless DC motor. At the rated speed, the core loss of amorphous alloy permanent magnet brushless DC motor is only 6% of the output power [6].

At present, there are a variety of motor design optimization methods, such as using ant colony algorithm, genetic algorithm and other intelligent algorithms, but this kind of method has a high learning threshold and needs long-term professional learning [7], [8]. The Taguchi method is to simulate various interferences causing product quality fluctuation through orthogonal arrangement test and error factors. Through statistical analysis of various test schemes, find out the design scheme with the strongest anti-interference ability, the best adjustment, the most stable performance and reliability [9]. This method is widely used in various areas of engineering optimization. In the optimization design of motor, the traditional optimization method of motor is difficult to achieve multi-objective optimization. As a standardized and scientific method, Taguchi method can achieve local multi-objective optimization design of existing motor. The Taguchi method is applied to the optimization design of the permanent magnet synchronous motor, and the best design scheme is found through optimization experiment to improve the performance of relevant motor, which further improves the performance of

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permanent magnet synchronous motor in all aspects and makes the motor design more reasonable [10]. At present, there are a large number of practical motor optimization applications. In China, Wen Jia-bin of Harbin University of science and technology which optimized a permanent magnet motor based on Taguchi method, and the cogging torque of the motor was reduced by 31% in [10]. Wang Ai-meng and others from North China Electric Power University combined the Taguchi method and finite element software to optimize the air gap and permanent magnet size of "U" rotor built-in permanent magnet motor. After optimization, the motor performance was greatly improved, which verified the effectiveness of Taguchi method in [11], Wuhan University of technology and Liuzhou Wuling Automobile Industry Co., Ltd. cooperated to optimize a permanent magnet motor for electric vehicles by Taguchi method. After optimization, the performance of the motor has been greatly improved and applied to engineering practice, which verifies the practicability and efficiency of Taguchi method in [12]. Cheng Peng and others from Harbin Engineering University cooperated with China Shipbuilding Power Co., Ltd. to optimize the parameters of an 8.6MW synchronous generator by using Taguchi method in combination with finite element method. Through optimization, the motor efficiency was increased from 97.4244% to 98.0738% in [13]. Zhu Rong qiu of Jiangsu University and others optimized the bearingless permanent magnet motor with combined magnetic poles by Taguchi method. The research shows that the no-load air gap waveform of the motor has been improved and the torque fluctuation has been significantly reduced in [14]. In other countries, Sujin Lee, kyuseob Kim and others from Hanyang University in Korea obtained the robust optimal solution of the motor based on Taguchi method, which improved the product quality and reduced the mass production cost in [15]. Sung IL Kim of Nanchang former National University cooperated with young kyoun Kim of Samsung Electronics Co., Ltd. and Yeon Hwan Jung of Daewoo Precision Industry Co., Ltd. to optimize the design of built-in "S" and "V" rotor permanent magnet motors, and the performance of motor cogging torque has been greatly improved in [16].

Based on a 25kW, 1700 r/min three-phase permanent magnet motor, the motor model is established and the relevant simulation analysis is carried out. Taking the stator slot width, the depth of the stator slot, the length of the air gap, the pole arc coefficient and the thickness of the permanent magnet as the optimization factors, and the motor efficiency, the cogging torque, the torque fluctuation and torque generated by permanent magnet per unit mass are taken as the optimization target. Set up the Taguchi method optimization scheme, carry out simulation analysis on each scheme and calculate and analyze the relevant simulation data obtained, and finally obtain the optimal design scheme. Finally, the performance of the motor before and after optimization is compared and analyzed. The research shows that through this optimization design, the cogging torque of the motor is reduced by 53.45%, the torque fluctuation is reduced by 36.79%, the torque generated by the permanent magnet per unit mass is increased by 21.42%, the motor runs more stable, and the motor operation performance has been improved to a certain extent, At the same time, the feasibility of Taguchi method in the optimal design of new soft magnetic material motor is also verified, provides an idea for local multi-objective optimization of a new type of soft magnetic material motor.

II. Analysis of Motor Structure Model

Due to the special requirements of ships and warships working environment, there is a great demand for small-volume medium-low-speed high torque permanent magnet motor. At the same time, there are certain requirements for motor operation stability and reliability, so it needs low torque fluctuation and cogging torque. The application of new soft magnetic materials improves the efficiency of the motor, and then improves its endurance and long-distance navigation ability. The motor is mainly used in Underwater Unmanned Aerial Vehicles and other weapons and equipment. Based on a 25kW, 1700 r/min three-phase new soft magnetic material permanent magnet brushless motor for underwater vehicle designed in the early stage, the model of amorphous alloy 1k101 new soft magnetic material motor is established for simulation analysis. The initial structural parameters of the motor are shown in Table I:

TABLE I
Main initial Structural Parameters of the Motor

Name	Value
Rated power (kW)	25
Rated voltage (V)	380
Rated speed (R/min)	1700
Inner and outer diameter of stator (mm)	104/176
Inner and outer diameter of rotor (mm)	44/102
Slot and pole	12/10

The motor model is shown in Fig. 1. The preliminary finite element simulation test of the motor is carried out under the rated working condition of 1700 r/min. The measured motor performance parameters such as motor efficiency and cogging torque are shown in Table II.

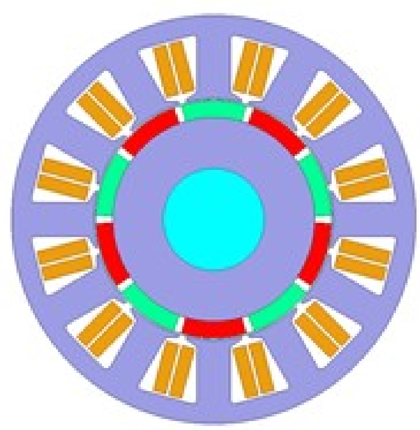

Fig. 1. Motor model diagram.

TABLE II
MOTOR OPERATION PERFORMANCE PARAMETERS

Performance	value
Efficiency (%)	98.05
Cogging torque (N.m)	2.09
Torque fluctuation (%)	1.05
Torque generated by permanent magnet per unit mass (N.m/kg)	36.46

III. MOTOR OPTIMIZATION BASED ON TAGUCHI METHOD

In terms of motor optimization design, the traditional method is to find the factors that affect a certain performance index, and then find the appropriate range for one-to-one design simulation. If there are too many factors, the test times of this method are too many, and the interaction between various factors is not easy to obtain. In this way, the optimization efficiency is very low, and the optimization result is not necessarily the optimal scheme [17], [18]. In addition, there are some optimization schemes using algorithms, such as improved particle swarm optimization algorithm, intelligent simulated annealing algorithm and genetic algorithm to optimize the motor structure. These methods usually optimize the overall situation of the motor. The optimization takes a long time and the algorithms are complex. The optimization cost of ordinary motor is slightly too high [17]-[19]. Taguchi (Taguchi) method is an orthogonal experimental technology designed by Dr. Xuanyi Taguchi and others at the Japan Institute of telecommunications in the 1950s [9]. This method has been widely used in various engineering optimization designs, including motor design optimization [9], [17]. Although the Taguchi method is a local optimization method, it can be optimized for multiple optimization objectives at the same time. Through the relevant experimental orthogonal table, the optimal combination of level values of each optimization factor that meets the optimization design can be obtained with as few experiments as possible. The optimization process of this method mainly includes determining the optimization factor, determining the scope and level value of the optimization factor, arranging orthogonal experiments, solving the average value and variance, and determining the optimal scheme [10].

A. Optimization Objectives and Optimization Factors

The optimization targets are the key index to improve the motor performance. The change of the optimization targets can see whether the optimization results are successful or not. The Taguchi method can be used for local multi-objective optimization. Cogging torque is an inherent property of permanent magnet motor, and its size affects the stability of motor operation. Therefore, high-performance motor needs low cogging torque [20]. Previous studies have shown that the application of new soft magnetic materials in the motor can effectively improve the efficiency of the motor. Therefore, the optimization objectives of this paper mainly focus on the torque fluctuation(K_m), the cogging torque(T_c) of the motor and the torque generated by the permanent magnet per unit mass(T_w), while ensuring that the efficiency (η) of the motor is basically unchanged. Therefore, this paper takes η , K_m , T_c , and T_w as the optimization objectives of this optimization design.

The optimization factor refers to the main parameters that can affect the optimization objectives. In view of the selection of optimization objectives and the structural characteristics of the motor [8], the optimization design will take the stator slot width b_0 , stator slot depth h_0 , air gap length δ , pole arc coefficient α and permanent magnet thickness h as the optimization factors, and optimize the motor performance by changing the value of each optimization factor. The different level values of each optimization factor are generally 3 ~ 5, and 5 different level values are selected for this optimization. Table III shows the specific parameter configuration of each level value.

TABLE III
OPTIMIZATION FACTORS AND PARAMETER CONFIGURATION

Parameter	b_0 /mm	h_0 /mm	δ /mm	α	h /mm
Level 1	2.8	22	0.8	0.85	6
Level 2	3	22.2	0.9	0.87	6.5
Level 3	3.2	22.4	1	0.89	7
Level 4	3.4	22.6	1.1	0.91	7.5
Level 5	3.6	22.8	1.2	0.93	8

These optimization factors will affect the η , K_m , T_c , and T_w . The ultimate purpose of optimization is to reduce the torque fluctuation and cogging torque of the motor as much as possible while maintaining the high efficiency of the motor and increase the torque generated by the unit mass permanent magnet of the motor. Torque fluctuation is used to measure the degree of torque fluctuation. According to the Chinese national standard "GB / T 21418-2008", its expression is shown in (1):

$$K_{\mathrm{m}} = \frac{T_{Max} - T_{Min}}{T_{Max} + T_{Min}} \times 100\% \tag{1}$$

Where T_{Max} is the maximum instantaneous torque and T_{Min} is the minimum instantaneous torque.

B. Orthogonal matrix and simulation experiment

According to the optimization objectives and optimization factors, the orthogonal experimental table of the optimization scheme is established. Use $L_n(q^t)$ to represent the code of the orthogonal table, in which the orthogonal table is represented by L , the number of experiments is represented by n , the number of optimization factors is represented by q^2 , and the horizontal value of each optimization factor is represented by 6. The standard orthogonal table of the same level value is generally $L_{25}(5^5)$. This orthogonal table can make different level values appear the same number of times in each column, and the horizontal number collocation between any two columns is also equal [5]. The optimized motor has five optimization factors, and each optimization factor contains five level values, so the Table IV represents the orthogonal matrix of this optimization. If according to the traditional motor optimization method, the various level values of each optimization factor are arranged and combined, and each scheme does a finite element simulation, it is necessary to do $5^5 = 3125$ finite element simulation experiments, which takes a huge amount of time. However, when using the Taguchi method to establish orthogonal matrix experiment, only $5^2 = 25$ finite element simulations are needed, which greatly improves the efficiency and cycle of motor optimization. The experimental orthogonal matrix is shown in Table IV, in which the values of the optimization factors correspond to the horizontal values of the optimization factors in Table III.

TABLE IV
EXPERIMENTAL ORTHOGONAL MATRIX TABLE

Number of tests	Experimental matrix				
	b_0 /mm	h_0 /mm	δ /mm	α	h /mm
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	1	5	5	5	5
6	2	1	2	3	4
7	2	2	3	4	5
8	2	3	4	5	1
9	2	4	5	1	2
10	2	5	1	2	3
11	3	1	3	5	2
12	3	2	4	1	3
13	3	3	5	2	4
14	3	4	1	3	5
15	3	5	2	4	1
16	4	1	4	2	5
17	4	2	5	3	1
18	4	3	1	4	2
19	4	4	2	5	3
20	4	5	3	1	4
21	5	1	5	4	3
22	5	2	1	5	4
23	5	3	2	1	5
24	5	4	3	2	1
25	5	5	4	3	2

According to the parameters of each experiment optimization factor shown in Table IV, change the corresponding design parameters in the finite element simulation software, carry out the finite element simulation experiment, get the simulation results of each time, and record the data of η, K_m, T_c and T_w obtained from each simulation, as shown in Table V.

TABLE V
FINITE ELEMENT SIMULATION RESULTS OF OPTIMIZATION OBJECTIVES

Number of tests	Result of experiment			
	η /%	T_c /N.m	K_m /%	T_w /(N.m/kg)
1	98.0198	1.0778	4.1261	43.8985
2	98.0345	1.8997	4.0490	39.8763
3	98.0463	2.3613	3.8142	36.4512
4	98.0529	2.6826	3.8124	33.5285
5	98.0561	3.0539	3.5061	30.9919
6	98.0769	2.7453	4.3361	34.1425
7	98.0814	3.1226	4.2711	31.5384
8	97.9950	3.3561	3.9579	40.3738
9	97.9840	1.0002	2.6561	41.0715
10	98.0680	2.2002	4.2985	37.1399
11	98.0391	3.8203	4.3443	37.3746
12	98.0250	1.1447	2.9047	38.2566
13	98.0329	1.9780	3.0823	35.1500
14	98.0976	3.1136	4.6617	32.1087
15	98.0270	3.4862	4.2744	41.0850
16	98.0649	2.2566	3.4743	33.0555
17	97.9695	2.8738	3.5240	42.2692
18	98.0647	3.8610	5.0538	38.0431
19	98.0717	4.2394	4.6619	34.8245
20	98.0593	1.2937	2.9015	35.8257
21	98.0267	3.8285	4.3291	35.8155
22	98.0981	4.5571	5.4684	32.5998
23	98.0864	1.4112	3.1584	33.6851
24	98.0053	2.5237	3.3023	43.0533
25	98.0190	3.2877	3.7994	39.1424

IV. NUMERICAL ANALYSIS

In order to analyze the influence of each optimization factor on the output torque, the torque fluctuation and the cogging torque of the motor at different levels, and the proportion of each optimization factor affecting the optimization target. According to the results of the finite element simulation experiment in Table V and the method of data statistics, the first step is to carry out the average value analysis, followed by the analysis of variance, observe the deviation degree, determine the proportion of each factor to the optimization target, and finally determine the optimal result.

A. Average Analysis

The overall average value of the simulation results of each performance index (optimization objective) is shown in formula (2), and the calculation results are shown in Table VI.

$$v = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{2}$$

In the formula, v represents the average value of all results of an optimization target in Table V; n represents the number of simulation experiments; v_i represents the value of an optimization target in the second experiment.

TABLE VI
OVERALL AVERAGE VALUE OF SIMULATION RESULTS

	η /%	T_c /N.m	K_m /%	T_w /(N.m/kg)
v	98.0441	2.6870	3.9107	36.8521

Then calculate the average value of the optimization target of each optimization factor at different levels. Taking the average value of cogging torque of air gap length under horizontal value 1 as an example, the corresponding calculation can be carried out according to formula (3)

$$v_{T_c}(\delta_1) = \frac{1}{5}(T_{c1} + T_{c2} + T_{c3} + T_{c4} + T_{c5}) \tag{3}$$

In the formula: $T_{c1} \sim T_{c5}$ represents the output torque value of the five simulation results of the output torque when the air gap length is at the level value of 1. Similarly, the average value of each optimization objective of other optimization factors at different levels can also be obtained. As shown in Table VII, it is the average value of each optimization objective of each optimization factor at different levels.

TABLE VII
AVERAGE VALUES OF OPTIMIZATION OBJECTIVES AT DIFFERENT LEVELS

Optimization factor	Level	η /%	T_c /N.m	K_m /%	T_w /(N.m/kg)
b_0 /mm	1	98.0419	2.2151	3.8616	36.9493
	2	98.0411	2.4849	3.9039	36.8532
	3	98.0443	2.7085	3.8535	36.7950
	4	98.0460	2.9049	3.9231	36.8036
	5	98.0471	3.1216	4.0115	36.8592
h_0 /mm	1	98.0455	2.7457	4.1220	36.8573
	2	98.0417	2.7196	4.0434	36.9081
	3	98.0451	2.5935	3.8133	36.7406
	4	98.0423	2.7119	3.8189	36.9173
	5	98.0459	2.6644	3.7560	36.8370
δ /mm	1	98.0696	2.9619	4.7217	36.7580
	2	98.0593	2.7563	4.0960	36.7227
	3	98.0463	2.6243	3.7267	36.8486
	4	98.0314	2.5456	3.5897	36.8714
	5	98.0138	2.5469	3.4195	37.0596
α	1	98.0349	1.1855	3.1494	38.5475
	2	98.0411	2.1716	3.6413	37.6550
	3	98.0419	2.8763	4.0271	36.8228
	4	98.0505	3.3962	4.3482	36.0021
	5	98.0520	3.8054	4.3877	35.2329
h /mm	1	98.0033	2.6635	3.8369	42.1360
	2	98.0283	2.7738	3.9805	39.1016
	3	98.0475	2.7548	4.0017	36.4975
	4	98.0640	2.6513	3.9202	34.2493
	5	98.0773	2.5916	3.8143	32.2759

According to the Table VII, in order to maximize the efficiency, minimize the cogging torque, minimize the torque fluctuation and maximize the torque generated by the permanent magnet per unit mass, the levels value combination of each optimization factor is $b_0(5)h_0(5)\delta(1)\alpha(5)h(5)$, $b_0(1)h_0(3)\delta(4)\alpha(1)h(5)$, $b_0(3)h_0(5)\delta(5)\alpha(1)h(5)$ and $b_0(1)h_0(4)\delta(4)\alpha(1)h(1)$ respectively.

Obviously, each optimization target has its own optimal combination scheme, and the four optimization targets have four combined schemes, so that the multi-objective optimal scheme cannot be determined. Therefore, it is necessary to continue to analyze the proportion of each optimization factor to the optimization target to determine the optimal solution. To obtain the specific gravity of the effect of each optimization factor on the optimization target, must continue to analyze the variance of the experimental results to obtain a better solution.

B. Variance Analysis

Variance is the average of the squared of the difference between the actual value and the expected value. It can represent the degree of deviation of the data center and can be used to measure the fluctuation of a group of data. In the case of the same sample size, if the fluctuation of the data is larger and more unstable, the value of variance will be larger; Conversely, the smaller the variance, the smaller the data fluctuation and the more stable [9]. Through the variance, the proportion of the influence of different levels of each optimization factor on the optimization target can be judged, and the optimal solution of motor optimization can be analyzed [10]. The variance calculation method is shown in formula (4) for variance calculation method:

$$S_A = \frac{1}{q}\sum_{i=1}^{q}(v_{A(i)} - v)^2 \tag{4}$$

In the formula: A represents optimization factors; S_A represents the variance of an optimization target in the case of an optimization factor A ; q represents the level number of each optimization factor, i.e. q =5; $v_{A(i)}$ represents the average value of an optimization target under the level 5 of an optimization factor i in Table VII; v represents the overall average value of an optimization target in Table VI.

Taking the average cogging torque of optimization factor air gap length at different levels value as an example, the corresponding variance value is calculated to explain formula (4). The result is shown in formula (5):

$$S_{T_c} = \frac{1}{5}\sum_{i=1}^{5}(v_{T_c(i)} - v_{T_c})^2 = 0.024794 \tag{5}$$

Similarly, the variance of each optimization objective of other optimization factors at the corresponding level can be calculated by formula (4). Table VIII shows the variance of each optimization objective of each optimization factor at the corresponding level.

TABLE VIII
VARIANCE AND PROPORTION OF OPTIMIZATION FACTORS AT CORRESPONDING LEVELS

Optimi-zation factor	η /%		T_c /N.m		K_m /%		T_w /(N.m/kg)	
	value	proportion %	value	proportion %	value	proportion %	value	proportion %
b_0	0.19364	99.4242	0.12805	12.5263	0.00321	0.69703	0.00302	0.02229
h_0	0.000003	0.00154	0.00288	0.28136	0.02083	4.52145	0.00401	0.02959
δ	0.000393	0.20189	0.02479	2.42544	0.21403	46.4679	0.01381	0.10187
α	0.0000405	0.02079	0.86190	84.3157	0.21693	47.0986	1.37280	10.1255

h	0.0006 85	0.35 155	0.00 461	0.45 119	0.00 559	1.21 492	12.1 642	89.7 207
Total	0.1947 62	100	1.02 223	100	0.46 059	100	13.5 578	100

C. *File Formats For Graphics*

According to the size of each variance value given in Table VIII and the proportion of the impact of each optimization factor on the optimization objective. It can be clearly seen that the slot width of the optimization factor has the greatest impact on the efficiency of the optimization target; Similarly, the pole arc coefficient has the greatest influence on the optimization target cogging torque and torque fluctuation, the permanent magnet thickness has the largest proportion and influence on the torque produced by the permanent magnet per unit mass permanent magnet. According to the analysis in Section "*A Average analysis*", in order to maximize the efficiency, minimize the cogging torque, minimize the torque fluctuation and maximize the torque generated by the permanent magnet per unit mass, the combination of levels values for each optimization factor are as follows: $b_0(5)h_0(5)\delta(1)\alpha(5)h(5)$, $b_0(1)h_0(3)\delta(4)\alpha(1)h(5)$, $b_0(3)h_0(5)\delta(5)\alpha(1)h(5)$ and $b_0(1)h_0(4)\delta(4)\alpha(1)h(1)$. According to the above analysis, the selection of the slot width of the optimization factor is based on the maximum efficiency, the selection of the pole arc coefficient of the optimization factor is based on the minimum cogging torque and torque fluctuation, the selection of the permanent magnet thickness of the optimization factor is based on the maximum torque generated by the permanent magnet per unit mass, and the selection of air gap and slot depth is based on the minimum torque fluctuation. After calculation and analysis, it can be obtained that the final optimal scheme combination of the level value corresponding to each optimization factor is: $b_0(5)h_0(5)\delta(5)\alpha(1)h(1)$. The parameters of the optimal combination scheme of the optimized optimization factors are shown in Table IX. For the convenience of comparison, the initial values corresponding to each optimization factor are also added to table IX. According to the obtained optimal scheme parameters, the structural parameters of the motor are adjusted accordingly, and then the finite element simulation analysis is carried out.

TABLE IX
HORIZONTAL COMBINATION OF OPTIMIZATION FACTORS AND THEIR PARAMETERS OF THE OPTIMAL SCHEME

Optimization factor	b_0 /mm	h_0 /mm	δ /mm	α	h /mm
Initial value	3.20	22.40	1.00	0.89	7.00
Optimal value	3.60	22.80	1.20	0.85	6.00

V. COMPARATIVE ANALYSIS OF MOTOR PERFORMANCE BEFORE AND AFTER OPTIMIZATION

The optimized motor model is established in the finite element software, the finite element simulation experiment is carried out, and the data before and after optimization are compared and analyzed. The comparison diagram of the motor output torque before and after optimization is shown in Fig. 2. The red solid line is the output torque curve before the motor optimization, and the blue dotted line is the output torque curve after the motor optimization.

Qualitatively analyze the output torque curve of the motor before and after optimization. From the comparison diagram, it can be seen that the overall output torque trend and size of the motor before and after optimization are basically the same, but because the curve is the torque of the whole process from the static state to the stable running state of the motor, the curve includes the two parts of the curve before and after steady-state operation, and the torque fluctuation is large before the motor runs steady-state, so the motor torque fluctuation is not obvious after the motor runs steadily. According to the Chinese national standard, Motor torque ripple refers to the torque fluctuation when the motor is running in a steady state. Therefore, the output torque of the motor after 40ms of steady-state operation is selected for processing and amplification, as shown in Fig. 3. It can be seen from Fig. 3 that the torque fluctuation of the motor is significantly reduced after optimization, which can effectively increase the stability and reliability of the motor operation.

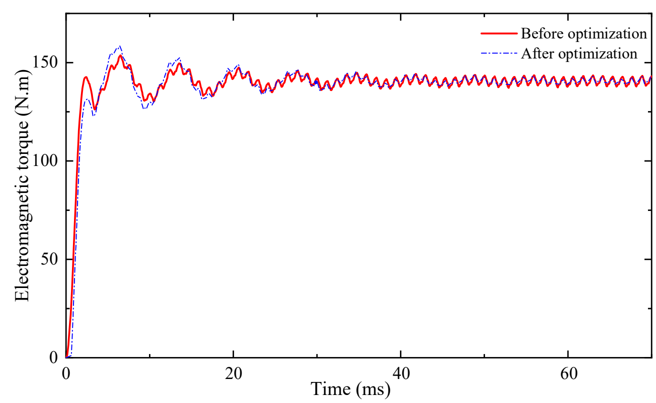

Fig. 2. Comparison diagram of motor output torque before and after optimization.

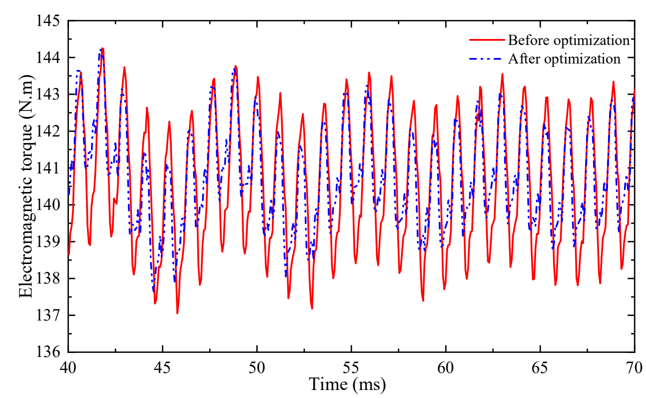

Fig. 3. Steady state torque diagram before and after motor optimization.

The above analysis shows that this optimization can effectively reduce the torque fluctuation of the motor. After the qualitative comparison and analysis of the optimized motor operation data and the corresponding data before optimization, the motor performance such as motor efficiency, cogging torque, torque fluctuation and torque generated by permanent magnet per unit mass are calculated quantitatively. The calculation results are shown in Fig. 4, Red slash filling is before optimization and blue filling is after optimization.

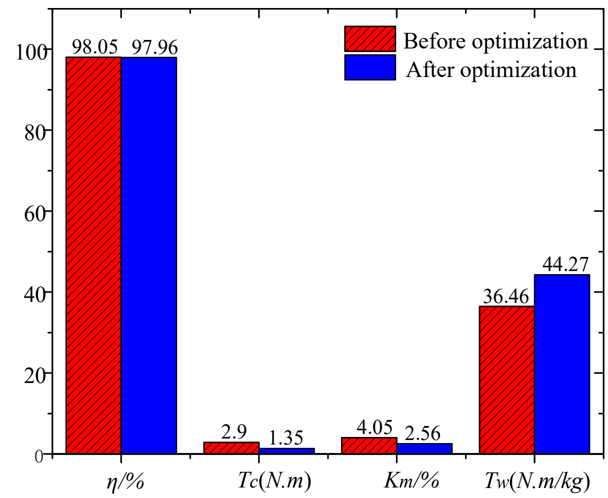

Fig. 4. Comparison of motor performance before and after optimization.

Through the analysis of Fig. 4., it can be clearly seen that after optimization, under the optimal scheme, the motor can keep the efficiency basically unchanged, the cogging torque of the motor can be reduced by 53.45%, the torque ripple can be reduced by 36.79%, and the torque generated by the permanent magnet per unit mass can be increased by 21.42%, the comprehensive performance of the motor has been significantly improved.

VI. Conclusion

Based on a 25kW, 1700r / min new soft magnetic material motor, taking stator slot width, stator slot depth, air gap length, pole arc coefficient and permanent magnet thickness as optimization factors, taking motor efficiency, cogging torque, torque fluctuation and torque generated by permanent magnet per unit mass as optimization objectives, using Taguchi orthogonal matrix method, Combined with finite element simulation. The local optimal scheme of motor design is obtained by processing and analyzing the obtained data. The research results show that:

1) While ensuring the high efficiency of the motor, the cogging torque of the motor is reduced by 53.45%, the torque fluctuation is reduced by 36.79%, and the torque generated by the permanent magnet per unit mass is increased by 21.42%. After optimization, the performance of the motor has been significantly improved;

2) The analysis of variance shows that the pole arc coefficient has the greatest influence on the cogging torque and torque fluctuation of the new soft magnetic amorphous alloy motor; For the torque produced by the permanent magnet per unit mass, the thickness of the permanent magnet has the greatest influence; For efficiency, the choice of notch width has the greatest impact on it; The selection of air gap and groove depth of the optimal scheme is based on the minimum torque fluctuation;

3) The application of amorphous alloy in permanent magnet motor can further reduce the core loss of motor, improve the efficiency of motor, and improve the endurance capacity and strike range of weapons and equipment. After optimization, the cogging torque and torque ripple of the motor are significantly reduced, the torque generated by the permanent magnet per unit mass is significantly increased, the motor design is more reasonable and the performance is more superior, which further expands the application scope of amorphous alloy in the field of motor. At the same time, it conforms to the general trend of energy conservation and emission reduction advocated by the world, and helps the development of "emission peak and carbon neutrality" in China. At the same time, the optimization design verifies the feasibility and effectiveness of Taguchi method in the optimization design of new soft magnetic material motor, provides a new idea for the optimization design of new soft magnetic material motor, and can also provide a reference for the optimization design of similar motors.

References

[1] X. H. Wang, "Adjustable speed permanent magnet synchronous motor," in Permanent magnet motor, 2nd ed, vol 10, Beijing, China 2011, pp, 290-294.

[2] Z. Q. Zhu, Y. X. Li, "Modularity techniques in high performance permanent magnet machines and applications," *CES Transactions on Electrical Machines and Systems*, vol. 2, no. 1, pp. 93-103, Mar. 2018.

[3] Q. Y. Wang, J. W. Lu, S. X. Jiang, "Research summary of amorphous alloy motor" *Electric Drive for Locomotives*, vol. 03, pp. 10-13, 2014.

[4] Z. Sun, "Research on optimal design and temperature field analysis of new amorphous alloy high speed permanent magnet motor," Ph.D. dissertation, Dept. Electron. Eng., North China Electric Power University, Beijing, China, 2019.

[5] M. J. Liu, Z. Sun, T. Zhang, et al, "Calculation and analysis of no-load stator iron loss of High-speed permanent magnet machine with amorphous alloy stator core," *Journal of North China Electric Power University*, vol. 05, no. 45, pp. 77-82+91, 2019.

[6] P. Chen, J. Chen, Y. Liao, et al, "Vibration and noise of High-speed amorphous alloy permanent magnet synchronous motor," in *Proc. of 2018 21st International Conference on Electrical Machines and Systems (ICEMS)*, Jeju Island, South Korea, 2018, pp. 318-322.

[7] B. M. Kumar, R. B. Ashok, "Soft computing using GWO (Grey Wolf Optimization) for the performance improvement of High-speed brushless DC motor," in *Proc. of 2018 International Conference on Emerging Trends and Innovations in Engineering and Technological Research (ICETIETR)*, Ernakulam, India, 2018, pp. 1-6.

[8] J. Gao, L. Dai, W. Zhang, "Improved genetic optimization algorithm with subdomain model for multi-objective optimal design of SPMSM," *CES Transactions on Electrical Machines and Systems*, vol. 2, no. 1, pp. 160-165, Mar. 2018.

[9] F. Z. Zeng, X. Zhao, "Taguchi method and its standardized design," *Machinery Industry Standardization & Quality*, vol. 11, pp. 7-9, 2003.

[10] J. W. Wen, L. Yu, "Application of Taguchi method in structural optimization of permanent magnet synchronous motor," *Journal of Harbin University of Science and Technology*, vol. 05, pp. 64-69, 2019.

[11] A. M. Wang, Y. Wen, "Application of Taguchi method in optimal design of built-in permanent magnet synchronous motor," *Journal of North China Electric Power University (NATURAL SCIENCE EDITION)*, vol. 43, no. 05, pp. 39-44, 2016.

[12] A. G. Han, Z. Yuan, Q. X. Zheng, et al, " Application for Optimal Designing of Interior Permanent Magnet Synchronous Machines by Using Taguchi Method," *Automotive practical technology*, vol. 06, pp. 40-44, 2019.

[13] P. Cheng, X. J. Yang, H. Lan, et al, "Design and efficiency optimization of synchronous generator using finite element method and Taguchi

method," *Journal of electrical machinery and control*, vol. 23, no. 02, pp. 94-99+104, 2019.

[14] R. Q. Zhu, Y. O. Cheng, "Rotor optimization design of bearingless permanent magnet synchronous motor based on modular poles," *Electric Machines and Control*, vol. 24, no. 03, pp. 123-130, 2020.

[15] S. J. LEE, K. Kyuseob, Sugil. Cho, et al, "Optimal design of Interior permanent magnet synchronous motor considering the manufacturing tolerances using taguchi robust design," *Iet Electric Power Applications*, vol. 08, no. 01, pp. 23, 2014.

[16] S. Kim, J. Y. Lee, Y. K. Kim, J. P. Hong, et al, "Optimization for reduction of torque ripple in interior permanent magnet motor by using the Taguchi method," *IEEE Transactions on Magnetics*, vol. 41, no. 5, pp. 1796-1799, May. 2005.

[17] Y. F. Zhang, Q. P. Meng, T. Su, et al, "Optimal design of dual redundancy permanent magnet synchronous motor based on Taguchi method," *Micromotors*, vol. 54, no. 09, pp. 37-42, 2021.

[18] S. Chen, Z. Zhang, J. X. Li, et al, "Multi-objective optimization design of a permanent magnet synchronous motor based on Taguchi method," *Micromotors*, vol. 54, no. 07, pp. 17-22, 2021.

[19] Y. C. Liu, W. M. Liu, H. H. Guo, "Optimal design of permanent magnet synchronous propulsion motor based on Taguchi method," *Small & Special Electrical Machines*, vol. 46, no. 03, pp. 18-20, 2018.

[20] F. Liu, X. Wang, Z. Xing, A. Yu and C. Li, "Reduction of cogging torque and electromagnetic vibration based on different combination of pole arc coefficient for interior permanent magnet synchronous machine," *CES Transactions on Electrical Machines and Systems*, vol. 5, no. 4, pp. 291-300, Dec. 2021.

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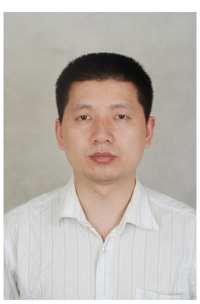

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