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Optimizing performance parameters of Halbach array rotor based on Taguchi algorithm

Ruiguang Yu, Zaixin Wu*， Yaxiang Wang , Huabing Li

Lanzhou University of Technology, School of Mechanical and Electrical Engineering, Lanzhou, 730050,China

Abstract

Due to the long development cycle and high cost of aeronautical motor, the performance parameters of the rotor with Halbach array structure are optimized by Taguchi algorithm. The performance parameters mainly include the thickness of magnetic steel, the number of blocks per pole as well as magnetizing angle. The evaluation index of the optimized parameters is that the volume of the magnetic steel used is the smallest, the air gap magnetic density is the largest and its shape is closest to the sinusoidal. The experimental group is verified by finite element method. Finally, the rotor structure parameters satisfying the high power density and high air gap magnetic density of aeronautical motor are determined, which shortens the product development cycle and reduces cost of manufacture.

Keywords: Aero motor; Halbach array; Taguchi; finite element method; performance parameter optimization

1. Introduction

In recent years, aero car has become a solution to traffic problems, and the research on aero car has become a hot topic of modern automobile enterprises, electric aero car has become an important field of investigation. Therefore, the study of aero-electric drive system has practical significance.

Motor is one of the vital components of aero-electric drive system. For the harsh working environment and the extremely sensitive requirement of volume and weight, and the high electromagnetic load of the aeronautical motor, the light weight of the aeronautical motor body is the serious problem we meet in the design [1].

* Zaixin Wu. Tel.: **+86-139-1978-5913**.
E-mail address: OrinYu@outlook.com

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The light weight of traditional motor is mainly focused on rotor, housing, and mount and stator. Solutions such as shaft opens pore will decrease strength of shaft; the housing, mount and stator achieve lightweight are depend on the way of developing new materials [2-4]; so the process of motor lightening is slow and the problem can not be solved fundamentally

In this paper, for the rotor with Halbach array permanent magnet designed for aero car, Taguchi algorithm is proposed to optimize the height of Halbach array magnetic steel to reduce the volume of magnetic steel, and then reduce the curb weight of motor. At the same time, the number of Halbach arrays and magnetizing angle of magnetic steel are analysed. The optimal number of blocks per pole and the optimal magnetizing angle are determined to produce more larger and most uniform air gap flux density.

2. Structure of motor for aero car

According to the permanent magnet structure of rotor, it can be divided into integral type and discrete type as well as some new types which have been developed in recently. Compared with the integrated structure, the discrete structure has a relatively simple manufacturing process and is mostly used in the Halbach structure. Since the rotor structure will be used in practical applications, and then considering the realization of the later manufacturing process, the discrete Halbach array structure is used in this rotor. The inner rotor with Halbach array permanent magnet synchronous is original designed in this paper, as shown in Fig .1(a).

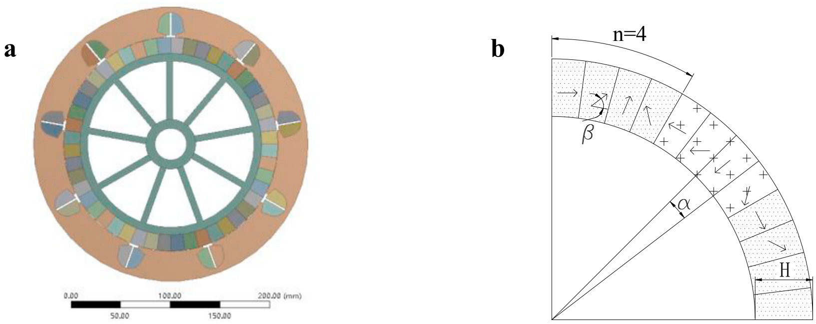


Fig. 1. (a) Cross section structure of motor; (b) Parameter diagram of Halbach array rotor.

The main parameters of rotor with Halbach array are shown in Fig. 1(b). Where n is the number of blocks per pole, H is the height of the magnetic steel, β is the magnetizing angle, ∂ is the angle of the center of the pole occupied by a piece of magnetic steel. In original design, the rotor with Halbach array of aero car motor is composed of 4 magnetic steel blocks per pole. The main structural parameters of the rotor are shown in Table 1.

Table 1. Rotor structure parameters of aero car motor.

Parameter name	Symbol	Value	Parameter name	Symbol	Value
Diamete of rotor yoke	D_1	182.9mm	Length of magnetic steel	L	34.5mm
Inner diamete of rotor yoke	D_2	168mm	Number of magnetic steels in per pole	n	4
External diameter of shaft	D_3	50mm	Polar angle of monolithic magnetic	∂	7.5°
Inner diameter of shaft	D_4	32mm	Angle of magnetization	β	45°

3. Optimization performance parameters of rotor based on Taguchi algorithm

3.1. Basic principle of Taguchi algorithm

The Taguchi algorithm proposed by the quality control expert Taguchi Gen'ichi in Japan. Its basic principle is based on orthogonal test and signal-to-noise ratio (SNR) technology. Although the Taguchi algorithm is a kind of local optimization algorithm, it can realize the optimization of multiple objectives at the same time. The greatest advantage of the algorithm is that it can use the least number of experiments, synthesize the optimal solution of multiple objectives, and then use the orthogonal experimental table. Thus, the optimal solution of multiple targets is obtained [5]. Because of the long development cycle and high cost of manufacture of the aero car motor, the Taguchi algorithm can be used to optimize the rotor of the motor in a shorter cycle. The technical route of rotor structure optimization by using Taguchi algorithm is shown in Fig. 2.

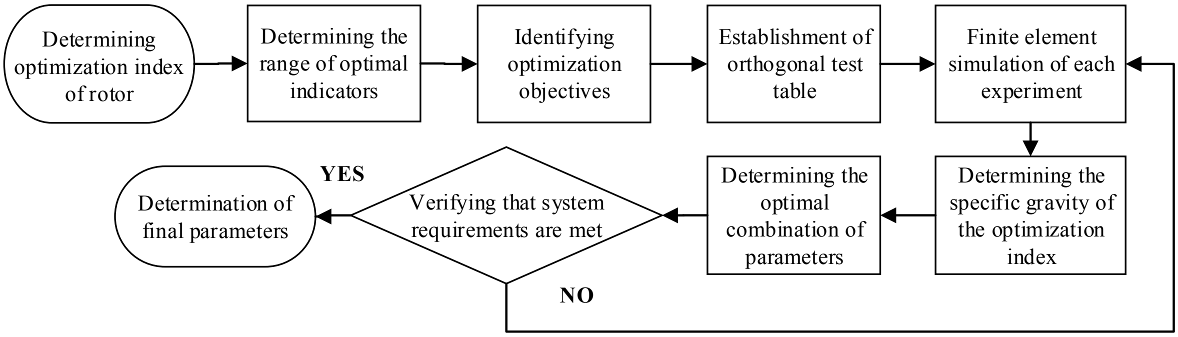


Fig. 2. Technical route diagram for optimization of Taguchi algorithm.

3.2. Optimization of Halbach array magnetic steel

In the Taguchi algorithm, the variation values of the optimization parameters are generally less than 5, and each parameter is named level 1, 2, 3 respectively according to the order from small to large. About traditional permanent magnet synchronous motor, in order to increase the air gap flux density and torque as well as power density of the motor, the thickness of the permanent magnet should be increased as much as possible, but high thickness of the permanent magnet will lead to high curb weight of motor. Therefore, the first optimization index determined in this paper is the thickness of permanent magnet. In discrete Halbach array structure, the number of blocks per pole has a great influence on the overall air-gap magnetic field, so the number of blocks per pole magnetic steel is determined as the second optimization index. In theory, the smaller magnetizing angle as well as the more the number of magnetic steel blocks per pole of the permanent magnet will produce the air gap magnetic flux density with closer sinusoidal shape. However, considering the actual manufacturing process and reducing the difficulty of production, the magnetizing angle can not be infinitely small, so the third optimization index is the magnetizing angle of permanent magnet. At that time, three optimization parameters are selected, and each parameter has 4 levels. In order to improve the accuracy of the range of horizontal values, the power correction coefficient λ is proposed , here λ is the ratio of peak power to rated power. And the range of the level will be determined linearly according to the correction coefficient.

In this paper, the optimization objective is to minimize the volume of the magnetic steel, which has achieved the goal of lightweight of rotor structure, and the air gap magnetic density is the largest and the shape is closest to the sinusoidal shape at the same time. The structural parameters and horizontal values of Halbach array determined in this paper are shown in Table 2.

Table 2. Level value of Halbach array structure index parameter.

Parameter name	H（mm）	n	β (°)
Level 1	16	2	30
Level 2	18.24	3	45
Level 3	20.48	4	60
Level 4	22.72	6	90

In this paper, 3 optimization parameters are selected and the value level has 4, so 16 kinds of combination results are needed. The orthogonal table is shown in Table 3. For the optimization objectives include volume of magnetic steel V, air gap flux density B_δ and sinusoidal air gap shape, and uniform distribution of magnetic force line, it is pointed out that torque characteristics of the motor is not considered because the main function of the motor is generator. The evaluation index models are as follows:

Table 3. Orthogonal list.

TN	H	n	β	TN	H	n	β	TN	C	n	β	TN	H	n	β
1	1	1	1	5	2	1	2	9	3	1	3	13	4	1	4
2	1	2	2	6	2	2	1	10	3	2	4	14	4	2	3
3	1	3	3	7	2	3	4	11	3	3	1	15	4	3	2
4	1	4	4	8	2	4	3	12	3	4	2	16	4	4	1

For the volume of magnetic steel, it should have the characteristics of small, and its evaluation index function is as follows:

$$V=\pi L\left((\frac{D_1}{2}+\mathrm{H})^2-(\frac{D_1}{2})^2 \right) \tag{1}$$

In this paper, an analytical method is proposed according to the physical method for the air gap flux density, and B_δ to be large. The calculation is as follows:

Calculation of polar arc coefficient α_i :

$$\alpha_i=\frac{b_p+2\delta}{\tau} \tag{2}$$

Where τ is the arc length, δ is the air gap length and b_p is the polar distance of each pole magnetic steel which near the air gap side.

Calculation of the air gap flux waveform coefficient K_Φ :

$$K_\Phi=\frac{8}{\alpha_i\pi^2}\sin\frac{\alpha_i\pi}{2} \tag{3}$$

Calculation of no-load flux $\Phi_{\delta 0}$:

$$\Phi_{\delta 0}=\frac{E_0}{4.44fNK_{dp}K_\Phi} \tag{4}$$

Where f is the rated frequency, N is the series turns in per phase winding, and K_{dp} is the winding factor. E_0 is the no-load electrodynamic force .

Calculation of air gap magnetic density B_δ :

$$B_\delta=\frac{\Phi_{\delta 0}}{\alpha_i\tau L_{ef}}\times 10^3 \tag{5}$$

Where L_{ef} is the effective length of the core.

The sinusoidal shape of air gap magnetic density is evaluated according to the waveform of the motor phase back EMF, and the distribution of magnetic force line is determined by finite element analysis.

4. Finite element experiment verification

Combined with the actual design process of the motor, the ideal experimental scheme group is determined by Taguchi algorithm. According to the actual situation, the unreasonable combination in orthogonal table is eliminated, and the model is established for the practical production group, further finite element analysis is done. The 13 to 16 group in Table 3 is verified by the finite element method. The B_δ is obtained by analytical calculation, the results are 1.1340 T, 1.3085 T ,1.6060 T, and 2.3574 T, the flux density of air gap has shown an increasing trend. Through the finite element analyse, the distribution of the back EMF waveform in the grouping experiment is shown in Fig. 3, and the distribution of the magnetic force line is shown in Fig. 4.

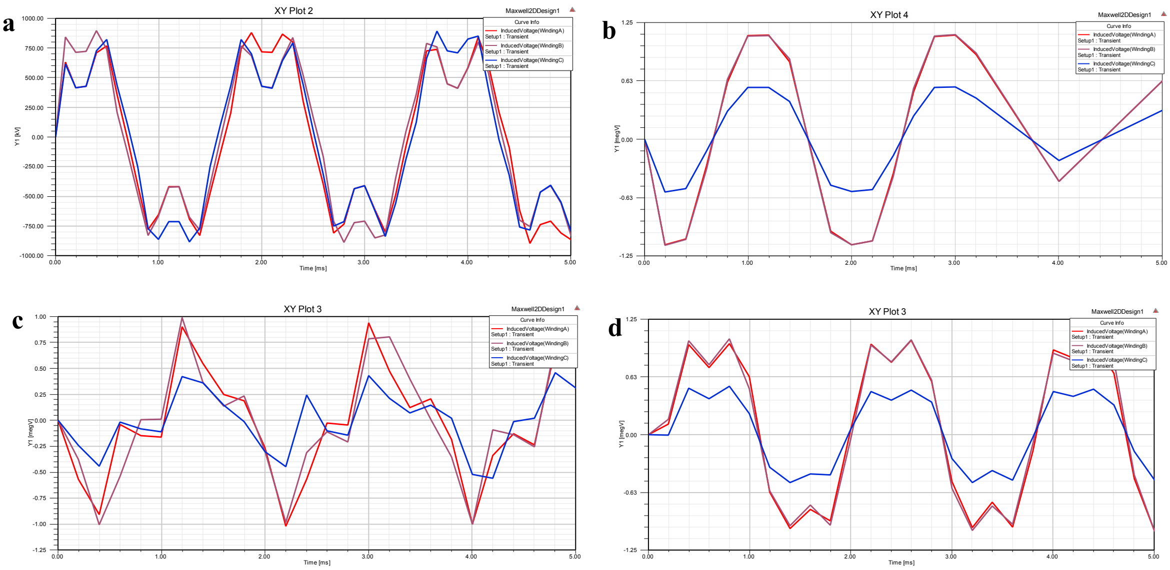
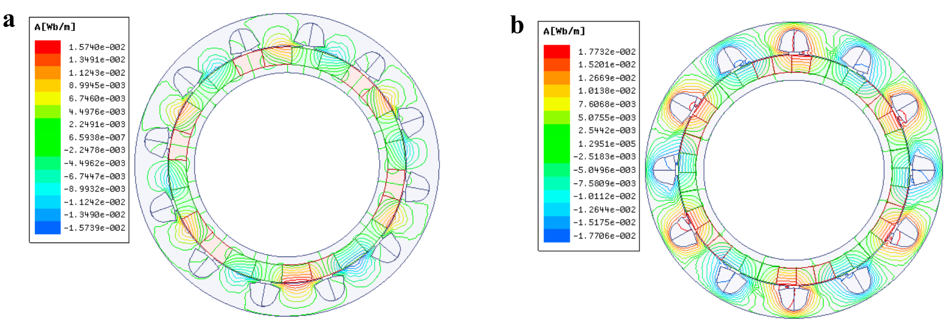


Fig. 3. Phase back EMF (a) TN 13; (b) TN 14;(c) TN 15; (d) TN 16.

Fig. 3 shows that the Halbach array PMSM can produce a sinusoidal phase back EMF. There are sharp-pointed distribution of the phase back electromotive force, which are mainly due to the transition and discontinuity of magnetizing direction of the block. The phase back EMF distribution on both sides of the peak can be transit gently. By synthesizing the distribution of the above waveforms, we can summarize that the waveforms in Fig.3. (b) are excessively smooth, showing good sinusoidal characteristics and having better generation characteristics.



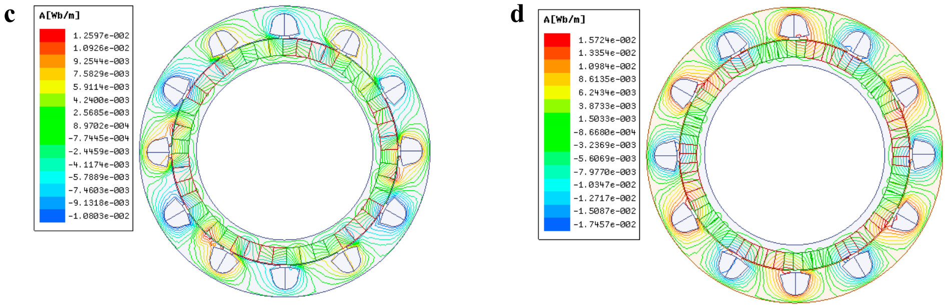


Fig. 4. Magnetic force line distribution (a) TN 13; (b) TN 14;(c) TN 15; (d) TN 16.

It is shown in Fig. 4 that the Halbach structure can produce a more uniform magnetic line of magnetic force and have good closeness per pole. The local unidirectional magnetic force line appears in Fig. 4 (a) and (b) at the axial junction of the magnetic steel block, mainly for the existence of radial magnetization. According to the distribution of the magnetic force line above, it can be sum up that the distribution of the magnetic force lines at each pole of (b) and (d) is denser and has more regular the shape.

In order to satisfy the operation of the motor under peak power, the thickness level of magnetic steel should meet level 3 and above, and determined the final level of magnetic steel thickness should be level 3 in order to reduce the curb weight of motor. By comparing the waveform of the phase back EMF and the distribution of magnetic force line in Fig.3 and Fig.4, it is determined that the 14 and16 of TN are the best experimental group. Considering further reducing the actual production and cost of manufacture and reducing the difficulty of the production process, it is determined that the Halbach array structure designed in this paper adopts the magnetic steel thickness is level 3, the number of blocks per pole are level 2, and the magnetizing angle is level 3. That is, the thickness of magnetic steel is 20.48 mm, the number of blocks per pole are 3 blocks, and magnetizing angle is 60°. The rotor has better comprehensive performance to be designed.

5. Conclusion

In this paper, on the premise of satisfying the high power density and high air gap flux of the aeronautical motor, the optimum objective is to minimize the volume of the magnetic steel used and to produce the largest density of the air gap magnetic density and shape the closest sinusoidal wave form. By using Taguchi algorithm and finite element method which commonly used in engineering, the performance parameters of Halbach array are optimized. The results show that the Halbach array structure is divided into more blocks per pole and with smaller magnetizing angle, and it can shape the phase counter electromotive force with the closer sinusoidal, the more uniform and closed magnetic force line distribution can be obtained. Finally, it is determined that the structure parameters of Halbach array, which meets the performance requirements of the rotor and has the highest performance-to-price ratio, the parameters include magnetic steel thickness is 20.48mm, and each pole is divided into 3 blocks and each block with 60° magnetizing angle, which greatly shortens the development cycle of the product. This method has strong engineering practicability in this paper used.

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