Fast Torque Optimization Technology of Brushless Motor Using ANSYS Finite Element Software and Maxwell2D

Ping Chen¹*, Xiangran Chang¹
¹Shenyang Aerospace University, Shaoyang, 110136, China
*Corresponding author e-mail: 20160020@sau.edu.cn

Abstract. In recent years, due to the large-scale research and development of brushless DC motor and the gradually mature technology, the distribution range of its drive system in industrial production has also expanded, and has gradually become the development mainstream [1] in the field of industrial automation. With the continuous development of industry, the motor control has also emerged more and more ways [2]. The operation principle of external rotor brushless motor is studied, a typical 12-slot 14 extremely concentrated winding UAV motor is described, and the optimization design of tooth groove torque and torque pulse is analyzed. Using ANSYS finite element software and Maxwell2D magnetic field, Optislang compares the sensitivity of different pole arc coefficients, negative length, and the simulation results show the effectiveness of the optimization method to provide effective basis for motor optimization design.

Key words: Brushless Motor; Finite Element Analysis; Optislang; Optimization Design

1. Introduction
Permanent magnet brushless DC motor has the advantages of high power density, small volume and high efficiency. It has widely used [3] in many fields. High-precision motion control system is generally used in the motor. The robustness of the motor has a great impact on the control system of [4]. Therefore, the robustness of a motor is an important indicator to measure the performance of a motor system [5], and the equivalent magnetic circuit method and finite element method in the motor performance analysis are widely used in the motor analysis. The magnetic field analysis of motor using Maxwell and the groove torque is optimized combined with response surface analysis.

1.1. Mechanism of the torque generation of the 1. tooth groove
The tooth groove torque is due to the opening of the stator slot of the permanent magnetic brushless motor, so the motor is evenly distributed along the peripheral direction of the stator, and the energy of the air gap magnetic field changes with the rotation angle, whether the motor operates or not. The stronger the magnetic energy of the permanent magnet, the greater the groove torque is [6]. The groove torque is a function of the relative position of the fixed rotor, which is greatly related to the groove structure and size of the motor. Accurately considering the impact of the groove structure on the air gap magnetic field of the motor is the key to analyze the groove torque. Computing principle and
weakening method of tooth groove torque

The groove torque is the reciprocal relationship between the internal magnetic energy of the motor and the spatial position \( \alpha \). That is:

\[
T = T_{\text{cog}} = \frac{\partial W}{\partial \alpha}
\]  

(1)

The total magnetic energy is an expression provided by the air gap and permanent magnetic field that can be reduced to:

\[
W = \frac{1}{2\mu_0} \int_B \left( \frac{h_m}{h_m + g(\theta, \alpha)} \right)^2 dV
\]

\[
B^2_r(\theta) = B_{n0} + \sum_{n=1}^{\infty} B_n \cos(2n\theta)
\]

\[
\left( \frac{h_m}{h_m + g(\theta, \alpha)} \right)^2 = G_0 + \sum_{n=1}^{\infty} G_n \cos(n(\theta + \alpha))
\]  

(2)

Dute torque expression after air gap and permanent magnetic field Fourier analysis:

\[
T_{n_1}(\alpha) = \frac{\pi z L_{Fe}}{4\mu_0} \left( R^2_2 - R^2_1 \right) \sum_{n=1}^{\infty} G_n B_r \frac{n\pi}{2p} \sin(nz\alpha)
\]  

(3)

Note: The distribution of \( B_r(\theta) \)— permanent magnet magnet along the circular direction;
The distribution of the effective air gap length between the \( g(\theta, \alpha) \)— center line of the pole and the tooth centerline at \( \alpha \);
\( h_m \)— permanent magnet charge magnetism direction length;
\( L_{Fe} \)— armature iron core length;
\( \alpha \)— clip angle of magnetic pole center-line and tooth centerline;
\( p \)— polar log;
\( z \)— slot number;
\( R_1 \)— armature outer diameter;
\( R_2 \)— stator yoke internal diameter;
Several methods of weakening according to the principle of tooth groove torque calculation.

1.2. Methods of adjusting the stator structure parameters

Altering the amplitude of Gn where the stator structure plays a major role on the sute torque and thereby weakens the sute torque. The method mainly includes: changing the groove width, changing the shape of the teeth, unequal groove width, inclined groove, opening the auxiliary groove on the teeth, etc.

1.3. Method of changing the magnetic pole parameters

The method of changing the magnetic pole parameters is to achieve the purpose of reducing the groove torque by changing the amplitude of the Brn acting on the groove torque. Methods include: change the pole arc coefficient of magnetic pole, using unequal thick permanent magnet, pole offset, oblique pole, pole segmentation, combination and unequal pole arc coefficient.

2. Motor design

Aoding to the main design indicators of brushless motor, the analysis results of magnetic circuit method are calculated using rmxprrt rapid modeling. By analyzing the main motor parameters such as currentcc density, no-load magnetic density air gap and motor characteristics and adjusting motor size and winding parameters, the motor design scheme requires that the rated power is 20w, rated speed of
7000rpm, rated torque of 0.0283n. The motor structure is shown below:

![Motor Structure Image](image.png)

**Figure 1. Motor Model**

3. Optislang

2.1. Optimize the process

Optislang is the method toolkit[7] for performing parameter sensitivity analysis, multidisciplinary optimization, robustness, reliability, and optimization design. Establish a high-precision prediction meta-model, analyze the parameter sensitivity, automatically recommend the most appropriate optimal algorithm according to the input parameters and the optimization objectives, and finally realize the product robustness and reliability evaluation. Define multiple optimization criteria (objective function) constraint functions based on input variables to limit the design space.

\[
\begin{align*}
    f_1(x) & \rightarrow \min \\
    f_n(x) & \rightarrow \min \\
\end{align*}
\]

\[
g_k(x_1, x_2, \ldots, x_n) = 0; k = 1, m_e
\]

\[
h_l(x_1, x_2, \ldots, x_n) \geq 0; l = 1, m_u
\]

(4)

2.2. Sensitivity analysis

The model uses the LHS Latin supercube to sample the motor factors, partition the sample space, and uses the cross-validation algorithm to calculate the CoP prediction model for the percentage of variation. Advantages CoP increases with the number of samples, with no false exact phenomenon, and CoP can accurately evaluate the regression quality for both interpolation and regression models. Sampling analysis of the variable polar arc coefficient, negative length, and permanent magnet thickness found that the percent sensitivity of the three variables to the tooth groove torque and the torque was 78%, 4%, and 18%, respectively. Negative length had less effect on the target function and does not participate in optimization. The cop assessments of torque, tooth groove torque, and rotational speed were 99%, 99.6%, and 99.1%, respectively.

\[
SS_{E}^{prediction} \text{ is the sum of squared prediction errors.}
\]

\[
SS_{E}^{P} \text{ is the sum of squared prediction errors.}
\]

(5)

\[
CoP = 1 - \frac{SS_{E}^{Prediction}}{SS_T}
\]

(6)

Parameter filtering: search the optimal parameter subspace to realize the design space dimension reduction. Regression algorithm is preferred: compare multiple regression algorithms (classical moving least squares and interpolated mobile least squares / linear and quadratic polynomial regression) to
determine the regression model with the best fitting accuracy.

**Figure 2.** Fitting the predicted quality coefficient

**Figure 3.** Cop mass coefficient

### 2.3. Response surface analysis

The response faces of the three variables, power, torque, groove torque and em, permanent magnet thickness mt, negative length off, are shown in Figure 4.5.

The PSO optimization analysis shows that the polar arc coefficient has the greatest impact on the tooth groove torque of the motor, followed by the thickness of the permanent magnet, which directly affects the cost, and the optimal combination of the optimal permanent magnet thickness and the polar arc coefficient is shown in Table 1.

**Table 1. Variable Parameters**

| Argument: Independent variable | Constrained Condition |
| --- | --- |
| (Percentage of) pole embrace em | 0.63 < em < 0.8 |
| Negative length of off/mm | 0 < off < 5 |
| Permanent magnet thickness is mt/mm | 1 < mt < 2 |

**Figure 4.** Power and pole arc coefficient and permanent magnet thickness

**Figure 5.** Tooth slot torque and pole arc coefficient and permanent magnet thickness
Figure 5. Torque and polar arc coefficient and permanent magnet thickness.

2.4. Optimize the results

Table 2. Optimal combination of structural parameters

| (percentage of) pole embrace | Foremagnet thickness (mm) |
|------------------------------|---------------------------|
| Initial value 0.7            | 1.2                       |
| Optimization value of 0.73   | 1.1                       |

According to the optimized structural parameters in Table 2, the finite element model was established in Maxwell2D, the motor tooth groove torque is analyzed, and the results agree with the optimization results.

Figure 6 compares the groove torque of the two, and the peak value of the initial finite element design is 0.5n.m, response surface optimization optimization predicts the structural tooth groove torque of 0.327n. The m, was decreased by 40% with the initial design.

Figure 6. Finite-element simulation comparison
3. Concluded
Using the outer rotor brushless motor with 12 groove 14 poles, the motor analyzed the production mechanism of the motor groove torque, analyzed the sensitivity of the magnetic pole structure parameters of the motor using Latin supercube sampling with otislang, generated the predictive element model with high quality, then optimized the motor arc coefficient and permanent magnet thickness, and obtained an optimal combination. The finite element analysis results show that adjusting the structural parameters of the motor inhibited the groove torque of the permanent magnet motor. Therefore, sensitivity analysis and response surface optimization can be efficient and rapid design.

References
[1] Lin Yuesen, Wu Siying, Zhuang Jiayang, Lin Taimin. Design study of brushless DC motor fault online monitoring system [J]. Internal combustion engine and Accessories, 2021 (12): 95-96.
[2] Gao Peiw en, Li Qiankun, Liu Shengxin, Wang Hao, Wu Xusheng. Design of the Brushless DC Motor Control System Based on Proteus [J]. Electrician & Electrical Engineering, 2021 (05): 17-21.
[3] Zhou Fengzheng, Meng Qinglin, Meng Zheng, Wang Haoming, Zhu Xiaohui. Optimization Design and Experimental Study of High-speed permanent magnet brushless DC Motor [J]. Micromotor, 2019,52 (03): 5-8
[4] Wang Lin, Xiao Jun, Liu Zhou. Design and Simulation of IP Control of DC brushless motor based on Matlab [J]. Ship Electronic Engineering, 2021,41 (02): 82-84 + 104.
[5] Wanshan Ming, Wu Fang, Huang Shenghua. Initial position estimation of the permanent magnet synchronous motor rotor based on high-frequency voltage signal injection [J]. Chinese Electrical Engineering Journal, 2008,28 (33): 82-86.
[6] Zhou loves the beauty. Optimization of tooth groove torque design of automatic door brushless DC motor [J]. Mechanical and Electrical Engineering Technology, 2021,50 (04): 211-214 + 226.
[7] Meng Qinghui. Rapid chemical modeling and lightweight design based on Patran Command Language [D]. Dalian: Dalian Maritime University, 2019.