Optimal Design of Permanent Magnet Structure to Reduce Unbalanced Magnetic Pull in Surface-Mounted Permanent-Magnet Motors

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This work was supported in part by the Major Program of National Natural Science Foundation of China through the Project under Grant 51690183, and in part by the Tianjin College Innovation Team Training Program of China under Grant TD13-5039.

ABSTRACT For the surface-mount permanent magnet synchronous motors (SPMSM) with fractional slot concentrated windings, the winding distribution of per phase under different poles is uneven, which results in unbalanced magnetic pull (UMP) between the stator and rotor. UMP has an important impact on the performance and service life of the motor. In this paper, a new permanent magnet (PM) structure is proposed to reduce UMP and torque fluctuation of the fractional slot SPMSM. Furthermore, a 48p/54s SPMSM is taken as an example, the proposed PM structure is optimized by the Taguchi method which can comprehensively consider the control factors and noise factors. The effects of various variables and process error on UMP, torque fluctuation and robustness of results are analyzed respectively. Finally, the optimized PM structure is obtained, which improves the operation stationarity.

INDEX TERMS Fractional slot SPMSM, unbalanced magnetic pull(UMP), torque fluctuation, Taguchi method.

I. INTRODUCTION

SPMSM has the advantages of simple structure, low manufacturing cost, and convenient installation, which is widely used in practical projects [1], [2]. The use of fractional slot windings can reduce cogging torque and torque fluctuation, increase the operation stationarity. And reduce vibration, noise and control difficulties [3]. It is well known that the magnetic field in the motor can generate a magnetic pull between the stator and the rotor. Additionally in fractional slot motors, the number of slots per pole per phase is a fraction, which makes the magnetic field distribution produced by each phase under different poles uneven, and then the unbalanced magnetic pull (UMP) is produced [4]. The UMP may cause noise and vibration, aggravate bearing aging, and even lead to stator rotor contact, which has an important impact on the service life and performance of the motor [5], [6]. Therefore, it is necessary to reduce the UMP of SPMSM with fractional slot concentrated windings.

UMP is mainly caused by the adjacent harmonics of air-gap flux density. For a motor without rotor eccentricity, UMP will be produced when the adjacent harmonics of air-gap flux density are not all zero [7]. It is affected by the armature reaction field, mutual interaction, and the PM field [8]. At present, the researches on reducing UMP mainly focus on the optimization of armature reaction field by the arrangement of the stator winding, the slotting effect is neglected. Accordingly, the unbalanced force due to the PM field only cannot be predicted, as shown in [9], [10]. In [11], the influence of different damper winding configurations on UMP in salient pole synchronous machines with rotor eccentricity is investigated. And in [12], the UMP is reduced by controlling the field currents of each segment’s external circuits. However, the effect of the PM field should not always be easily ignored. In [13], it is noted that the change of slot width and pole shape can also reduce the radial electromagnetic force density and
then reduce the UMP. In [14], it is considered that the UMP is smaller when the PM magnetization is uniform. The UMP generated by the PM field is reduced by the optimal design of the PM structure, and its arrangement of winding and control method is simpler than the method of optimizing windings.

The torque fluctuation of motors has an impact on the stationarity under operation and the accuracy of control, especially in the light load and low-speed state. In recent years, many scholars have studied how to reduce the torque fluctuation of PMSM [15], [2], such as optimizing the pole slot matching and the rotor parameters [16]. In [17], it is pointed out that the cogging torque can be reduced by skew pole, and the skew pole angle and the axial segments number to minimize the cogging torque are determined. A novel consequent-pole permanent magnet (CPM) motor featuring N-S-iron-S-N-iron sequences is presented to eliminate the even-order harmonics of phase back electromotive force (EMF) and the unipolar leakage flux in the end region, which reduce the torque fluctuation [18]. Moreover, a method of using different PM width to reduce cogging torque and torque fluctuation of SPMSM is proposed in [19]. Through the analysis of the relationship between the different PM shapes and the torque fluctuation, it is concluded that the use of unequal thickness PM can effectively reduce the torque fluctuation [20]. On this basis, three kinds of PM shapes with unequal thickness are proposed in this paper. Meanwhile, different shapes are analyzed as variables.

The Taguchi method is a kind of local optimum design method that can realize the multi-objective optimization design, whose core idea is to select the appropriate orthogonal table according to the number of variable values for experimental design. The orthogonal experiments design makes the experiment points evenly distributed, orderly, and comparable, which can minimize the number of tests and save the experimental cost [21]. Compared with some optimization algorithms which need to express geometric constraints accurately by formula, it is more suitable for the optimization of the irregular structure with mutual constraints in the motor. At the same time, the influence of each optimization variable on the optimization objective and the relative importance of the influence can be intuitively analyzed through the mean value analysis and variance analysis of the experimental results, which is helpful to get a better understanding of the motor structure.

At present, the Taguchi method has been widely used in the motor field, such as being used for optimizing the pole-arc coefficient, PM thickness, and position to reduce the torque fluctuation [22]. There are optimizations of the pole arc coefficient, air gap length, thickness of PM, and the number of turns in series of each phase of an axial flux permanent magnet synchronous generator, so as the voltage regulation rate and wave distortion rate can be reduced and the generator the performance can be improved [23]. In [24], the internal circulation cooling path size is optimized by the Taguchi method in an enclosed permanent magnet motor, which achieves a better cooling effect. Besides, under the influence of the manufacturing process, the machining error of the motor will also affect the performance of the motor, especially some key structural variables, whose machining error will have a greater impact on the performance of the motor. An analytical model for studying the effect of machining errors on the torque fluctuation of SMSM has even been put forward in [25]. The sensitivity of structural parameters has also been analyzed in [26] and [27]. The noise factor is added when the Taguchi method is used to optimize the structural parameters of the motor to reduce the torque fluctuation [28]. In this way, the influences of the motor structure parameters, the inevitable change in the manufacturing process, and dimension tolerance are considered. And the signal-to-noise (S/N) ratio is used to measure the ability of the optimization target to resist the interference of noise factors. Therefore, when the Taguchi method is used to optimize the PM structure, the influence of the change of control factors and noise factors are both considered to ensure the optimized structure has better robustness in this paper.

The electromagnetic performance of a fractional slot SPMSM calculated by FEM is analyzed in this paper. To improve the operation stationarity of the SPMSM with fractional-slot concentrated windings, the unequal thickness PM structure with changed magnetization direction is proposed. The Taguchi method is used to optimize the proposed PM structure to further reduce the UMP and torque fluctuation. In the process of optimization, the influence of machining error is considered, and the expected small characteristic of the S/N ratio is taken as the index to evaluate each parameter. The best combination of structural parameters, i.e. the optimum design which makes the UMP and torque fluctuation small with good robustness is obtained, through the calculation of the S/N ratio, the analysis of average value and the analysis of contribution rate.

The motor with an optimized structure is suitable for the occasions with high requirements for motor running stability, such as the use with active magnetic bearing (AMB). Because the rotor has no mechanical support, it needs to reduce its torque fluctuation and UMP to ensure the stable operation of the motor system, which has the advantages of no mechanical contact, no lubrication, and no wear. The literature [29] and [30] give a more detailed introduction to this kind of combined use.

II. IMPROVEMENT OF PM STRUCTURE

In this paper, the relationship between the air-gap flux density and UMP is expounded by calculation formulas. And the improved PM structure is proposed to reduce UMP.

A. CALCULATION OF UMP

The electromagnetic force between the stator and rotor can be divided into radial components and tangential components. The UMP is the product of the electromagnetic force density and the side area of the corresponding cylindrical area. Radial component $\sigma$ and tangential component $\tau$ of electromagnetic force density can be calculated by the
radial air-gap flux density $B_r$ and tangential air-gap flux density $B_\alpha$, the expression is as follows:

$$\sigma = \frac{B_r^2 - B_\alpha^2}{2\mu_0}$$  \hspace{1cm} (1)
$$\tau = \frac{B_rB_\alpha}{\mu_0}$$  \hspace{1cm} (2)

where $\mu_0$ is the permeability of vacuum.

The cogging torque and electromagnetic torque of the motor can be obtained by the following formula under no-load and load conditions:

$$T = L_zr^2 \int_0^{2\pi} \tau d\alpha$$  \hspace{1cm} (3)

where $\alpha$ is the rotor rotation angle.

In the Cartesian coordinates, the $x$ component and $y$ component of the UMP are produced by the radial electromagnetic force density $\sigma$, and the expression is as follows:

$$F_x = rL_z \int_0^{2\pi} \sigma \cos \alpha d\alpha$$  \hspace{1cm} (4)
$$F_y = rL_z \int_0^{2\pi} \sigma \sin \alpha d\alpha$$  \hspace{1cm} (5)

The magnitude of the total UMP is expressed as:

$$F_t = \sqrt{F_x^2 + F_y^2}$$  \hspace{1cm} (6)

It can be seen from (4), (5), and (6) that the UMP may be reduced by reducing the radial component $\sigma$ of the electromagnetic force density.

**B. IMPROVEMENT OF PM STRUCTURE**

The radial and tangential components of air-gap flux density can be changed by adjusting the magnetization direction. Therefore, the appropriate radial and tangential components of air-gap flux density can be obtained by changing the magnetization direction, and then the radial electromagnetic force density can be reduced. The PM of SPMSM is directly adjacent to the air gap, hence the shape of PM will affect the distribution of the air gap flux field. And the torque fluctuation can be reduced by changing the PM shape. Therefore, this paper proposes an improved structure to reduce the UMP and torque fluctuation, as shown in Fig. 1.

**TABLE 1. Parameters of the motor.**

| Parameter                | Symbol | Value | Unit |
|--------------------------|--------|-------|------|
| Rated speed              | $n_s$  | 2.7   | r/min|
| Rated torque             | $T_s$  | 2.6   | Nm   |
| Pole pair number         | $P$    | 24    |      |
| Slot number              | $Q$    | 48    |      |
| Outer radius of rotor    | $R_a$  | 87.2  | mm   |
| Air-gap length           | $\delta$ | 1.3  | mm   |
| PM thickness             | $h$    | 1.5   | mm   |
| Effective length of motor| $l$    | 18.5  | mm   |
| Remanence                | $B_r$  | 1.19  | T    |

Fig. 3. shows that the torque fluctuation and radial electromagnetic force density both decreased by using the improved structure in Fig. 1. Therefore, this magnetizing mode and PM shape can effectively reduce the torque fluctuation and the UMP, which improves the stationarity under operation.
III. OPTIMUM DESIGN OF IMPROVED PM STRUCTURE

It is necessary to optimize the proposed improved PM structure to achieve better performance. The influence of the PM structure parameters and the processing error is considered. And the Taguchi method is used to optimize the improved PM structure.

A. OPTIMIZATION VARIABLES

Different unequal thickness PM shapes can be obtained as shown in Fig. 4, which is considered as an optimization variable. The shape of the PM in Fig. 4(a) is named S1, whose both sides coincide with the original equal thickness PM. The shape of the PM in Fig. 4(b) is named S2, whose outer edge vertex falls on the line between the eccentric center o’ and the lower edge of the original equal thickness PM. The shape of the PM in Fig. 4(c) is named S3, whose outer edge vertex falls on the line between the eccentric center o’ and the upper edge of the original equal thickness PM.

The selected optimization variables are shown in Fig. 5, according to the improved PM structure, the optimization variables are represented as $A, B, C$, and $D$ respectively. $A$ represents the pole-arc coefficient of the original equal thickness PM; $B$ represents the distance between the arc center o’ outside the PM and the motor center o; $C$ represents the magnetization direction; $D$ represents different PM shapes. The unique PM structure can be determined by taking the values of the above four variables. Copper consumption less than 10W is taken as a constraint condition.

The values of the above four optimization variables are determined according to the structural parameters of the motor. Therefore, three levels are selected in each variable factor averagely. And S1, S2, and S3 are used to represent three levels of PM shape $D$ respectively. The $L_9(3^4)$ orthogonal table is selected for control factors experiment design according to the number of factors (design variables) and the number of levels corresponding to each factor. The orthogonal experiment table of control factors is shown in TABLE 2.

There may be some errors in the pole-arc coefficient, the position of the outer arc center and the magnetization direction because of the influence of the processing technology. Therefore, the above three variables are considered as noise factors as well as control factors. And $\pm 2\%$ is selected as a processing error to determine the error range and establish a noise factor table, which represents different error situations. It is also designed according to the orthogonal table. The orthogonal experiment table of noise factors is shown in TABLE 3.

The variable $a$, $b$ and $c$ in TABLE 3 are divided into representatives the values of factors $A$, $B$, and $C$ in TABLE 2. For example, the values of $a$, $b$ and $c$ are respectively 0.7, 71 and 45° at the first group of the experiment in TABLE 2. Taking the control factor table as the exterior and the noise factor table as the interior, a total of $9 \times 9 = 81$ matrix experiments are conducted.

B. CALCULATION OF UMP EXPERIMENTAL RESULTS AND RESULTS PROCESSING

The torque fluctuation $K_{th}$ and UMP $F_r$ of each experimental group are calculated by FEM, the results are listed in TABLE 4 and TABLE 5 respectively.
In order to analyze the influence of various factors on torque fluctuation, UMP, and its robustness, it is necessary to calculate the S/N ratio and the average value of each experimental group.

1) CALCULATION OF S/N RATIO

The calculation of the S/N ratio is an important method of robust design. And different expressions are used in different experimental applications. The expected small characteristic of the S/N ratio is taken as the index to evaluate the design of each parameter. The larger the S/N ratio is, the smaller the torque fluctuation or the UMP is, the smaller the result fluctuation caused by machining error is.

The robustness is directly proportional to the S/N ratio, its expression is shown in (7):

$$\eta = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} z_i^2 \right)$$  \hspace{1cm} (7)

where $z_i$ represents $n_{th}$ measurements.

The S/N ratio calculation of the first group of experimental results of torque fluctuation in Table 4 is shown in (8):

$$\eta_{11} = -10 \log \left( \frac{1}{9} (K_{tb1}^2 + K_{tb2}^2 + \cdots + K_{tb9}^2) \right) = -10 \log \left( \frac{0.0186^2 + \cdots + 0.0171^2}{9} \right) = 35.89$$  \hspace{1cm} (8)

Similarly, the S/N ratio and the average value corresponding to the results of torque fluctuation and UMP of each experimental group are calculated and listed in Table 5.

In order to analyze the variation of the torque fluctuation, UMP, and result robustness for each level of each factor, the experimental results in Table 6 are calculated and analyzed for average value and contribution rate. And then the relative importance of the four factors on the torque fluctuation and UMP are compared.

2) ANALYSIS OF AVERAGE VALUE

Combined with Table 2 and Table 3, the average value of torque fluctuation $K_{tb}$ at each level of $A$ is calculated, in (9), (10), and (11).

$$l_{K_{tbA}} = \left( K_{tba1} + K_{tba2} + \cdots + K_{tba3} \right) / 3 = 0.0203$$  \hspace{1cm} (9)

$$l_{K_{tbA}} = \left( K_{tba4} + K_{tba5} + K_{tba6} \right) / 3 = 0.0166$$  \hspace{1cm} (10)

$$l_{K_{tbA}} = \left( K_{tba7} + K_{tba8} + K_{tba9} \right) / 3 = 0.0168$$  \hspace{1cm} (11)

Similarly, the average value of torque fluctuation, UMP, and S/N ratio at each level of each factor are calculated and the results are listed in Table 7.

The regular pattern of the torque fluctuation and UMP with various factors changes are plotted as Fig. 6. With the increase of factor $A$, the torque fluctuation and UMP decrease first and then increase; with the increase of factor $B$, the UMP decreases, and the torque fluctuation first increases and then decreases; with the increase of factor $C$, the torque fluctuation and UMP increase; with the increase of factor $D$, the torque fluctuation decreases, and the UMP increases first and then decreases. It can also be seen that when the torque fluctuation and UMP decrease, the S/N ratio increases concurrently, which represents this group of the experiment is less affected by the error factors and has good robustness. Therefore, the combination with a high S/N ratio can be selected as the optimal scheme.

It can be obtained from Table 7 and Fig. 6 that the combination of the level taken by each factor making the S/N
The ratio of torque fluctuation $\eta_1$ is largest is $A(2)B(3)C(1)D(3)$. And the combination of the level taken by each factor making the S/N ratio of UMP $\eta_2$ largest is $A(2)B(3)C(1)D(1)$. The combination of the level taken by each factor making the S/N ratio of torque fluctuation and S/N ratio of UMP largest is different. Therefore, the relative importance of each factor to the results is analyzed. And the selection of the level combination is considered both torque fluctuation and UMP.

3) ANALYSIS OF VARIANCE (ANOVA)

The ANOVA is a statistical analysis to determine the contribution of the factors in experiments. The sum of the S/N ratio under each level of each factor is shown in TABLE 8, the relative importance of each factor to the results of $\eta_1$ is analyzed.

| Factor | $K_0$ | $F_1$ | $P_1$% |
|--------|-------|-------|--------|
| A      | 5.78  | 16.29 | 9.25   |
| B      | 0.71  | 2.00  | 32.40  |
| C      | 28.08 | 79.14 | 39.95  |
| D      | 0.91  | 2.56  | 3.57   |
| Total  | 35.49 | 100   | 85.18  |

It can be seen in TABLE 9 and Fig. 6, that the most influential factor on torque fluctuation and unbalanced magnetic pull is $C$. With the increase of magnetization angle, torque fluctuation and UMP increase, and then the S/N ratio decreases. Besides, factor $B$ has a great influence on the UMP. The farther the distance between the inner and outer arc centers of unequal thickness PM is, the smaller the UMP is.

C. CALCULATION OF UMP OPTIMIZATION SCHEME OF THE IMPROVED PM STRUCTURAL

The combinations of levels taken by each factor for different optimization objectives are different. It can be seen from Table 9 that the relative importance of the effects of each factor on the torque fluctuation is $CADB$ from the largest to smallest. And the relative importance of the effects of each factor on the UMP is $CBAD$ from the largest to smallest. In these two combinations, factor $C$ selects the same level, $C(1)$, whereas the levels of factors $A$, $B$, and $D$ are different. It can be seen that the effects of factor $A$ on the torque fluctuation is larger than that on the UMP, hence the level taken by factor $A$ is to make the torque fluctuation smallest. The effects of $B$ and $D$ on the UMP are larger than those on the torque fluctuation, hence the levels taken by factors $B$ and $D$ are to make the UMP smallest. From the above, the levels taken by each factor are $A(2)B(3)C(1)D(1)$. The final optimized structure is shown in Fig. 7.

The percentage contribution to torque fluctuation of factor $A$ can be calculated by (14):

$$p_{1A} = \frac{SS_{\eta_1 A}}{SS_{\eta_1 T}} \times 100 = \frac{5.78}{35.49} \times 100 = 16.29 \%$$

Similarly, the sum of squares and the contribution rate for each factor to torque fluctuation and UMP can be calculated and the results are listed in TABLE 9.

The parameters and performances of the motor with the original structure, the improved structure, and the final optimized structure are compared. And the FEM calculation results are shown in Fig. 8, Fig. 9 and TABLE 10.

It can be seen from the results that the UMP and torque fluctuation of the motor is reduced when the proposed struc-
It should be noted that the back EMF is reduced after optimization. To keep the rated torque unchanged, the current will be increased, which increases copper consumption. According to the data in TABLE 10, the copper consumption is 8.6 W, which is within the limit. At the same time, it can be seen that the optimized structure can also effectively reduce the cogging torque, which is beneficial to the improvement of motor performance.

**IV. CONCLUSION**

In this paper, the Taguchi method is used to optimize the PM structure of a fractional slot SPMSM, and a kind of optimized structure is proposed, which can effectively reduce the motor UMP and torque fluctuation, improves the operation stationarity. Besides, some conclusions are drawn as follows:

1) The geometric structure of the PM is complex, and the influence of the structural parameters on UMP and torque fluctuation is nonlinear.

2) Factor C, i.e. the direction of magnetization, has the largest influence on UMP and torque fluctuation, with contribution rates of 79.14% and 46.91%, respectively. When the magnetization angle is 45°, both UMP and torque fluctuation are the smallest.

3) Factor B, i.e. the distance between the center of the inner and outer circles of the pole has a great influence on the UMP, and its contribution rate is 38.04%. The larger the distance is, the smaller the UMP is.

The optimization PM structure proposed in this paper is determined based on the above conclusions. Through the FEM, it is proved that after using the optimization PM structure, the UMP and torque fluctuation of the motor is reduced, and the operation stationarity of the motor is effectively improved. The optimized structure may make the manufacture of permanent magnet more complex. However, for a high-performance motor that could be used on special occasions, the longer processing time is worth waiting for.

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