Operational range extension method for limited-angle torque motors with irregular slot numbers

Pengcheng Ma | Qian Wang | Yong Li | Shanlin Jiang | Meng Zhao | Ziliang Feng

Abstract
A modified model of a limited-angle torque motor (LATM) with irregular slot numbers is proposed for developing an operational range extension method for LATMs. The modified model is derived by considering the effects of the asymmetrical winding structure and magnetic flux leakage, which are validated by finite element analysis and experimental measurements. Based on the modified model, accuracy and time consumption of the simulation can be improved. For the operational range extension method, extended angle range selection theory and constraint conditions are proposed, and the relationship between the sinusoidal tracking characteristic and leading parameters is established by theoretical analysis. A simulation and a prototype machine experiment on an LATM using the new method are carried out. The results show that the proposed operational range extension method can reduce the weight and volume of the LATM without changing sinusoidal tracking characteristics, which proves the feasibility of applying the new method in the oscillating scan system to realize lightness and miniaturisation of the system.

1 | INTRODUCTION

The limited-angle torque motor (LATM) is a rotary actuator operating in a limited angle range [1–3]. Its topological structure is similar to that of the permanent magnet synchronous motor, but it has only one phase winding and runs with a single-phase current [4]. Because of its advantages of simple control and reliable operation, the LATM is widely used in the aerospace field [5–7]. The topologies of LATMs are various, and they have their own characteristics. However, all LATMs have a common characteristic, that is, the output torque is almost constant in a particular angle range, and this range is called the constant torque region [8–10]. Because of its excellent performance, the constant torque region is usually used as the operational range of the LATM [11,12]. Because of requirements for lighter and smaller equipment in the aerospace field, improving the power density of LATMs is a primary optimization objective [13].

However, the power density optimization method of LATMs usually has a negative effect on the excellent performance of the constant torque region. The method of applying the Halbach array to a radial magnetic flux LATM is proposed in [14]. This method is proven effective in improving the power density of the LATM, but it results in nonlinear torque change in the constant torque region. The operational range extension method using the linear region of the angle-torque characteristic is proposed in [15]. The power density of the LATM can be improved by this method, but the operational range includes both the constant torque region and the linear region, resulting in more complex torque characteristics. Such complex motor characteristics are acceptable in applications where control accuracy does not need to be high, such as the LATM following the step position signal in the aircraft servo valve [16]. However, when the LATM tracks the sinusoidal position signal within a large range of angles, the complex torque characteristics will have a negative impact on tracking accuracy. To suppress the negative impact of complex torque characteristics and achieve accurate tracking motion, two methods are usually adopted.

The first is a corresponding control method for adapting the complex characteristics [17]. A robust position controller is proposed for the LATM applied in fuel control of gas turbine engines [18]. This controller can realize semi-closed loop control of the LATM following the step position signal, but it is not suitable for high-precision applications. A repetitive control method in which the controlled variables follow periodic
reference commands is proposed to design the tracking control system of the LATM [19]. The LATM can achieve accurate position tracking at high frequency by this method. However, the operational range of the LATM controlled by this method is about $\pm 3.8^\circ$, which means that it may not meet the requirements within a large angle range. A sliding-mode controller with a system identification observer is used to improve performance in the position control of a voice coil motor [20]. As the voice coil motor is a kind of LATM, this control method is also of reference value for other LATMs. A robust output feedback control with high-gain observer is proposed to handle both model uncertainty and the angular-dependent nonlinear current torque relationship of the LATM with the cylindrical Halbach magnetic array in [17]. By this method, the LATM can track the sinusoidal position signal in the range of $60^\circ$, and the error is no more than 0.87%. This method has reference value for the control of the LATM with complex torque characteristics.

The second method establishes an accurate motor model, and then accurate control can be achieved based on the model [20–22]. The dynamic model of a pancake LATM-spring system is established in [23]. With consideration given to the nonlinear problem of friction, the model is proven accurate in experiments. A simplified field-circuit coupling method for an LATM with concentrated winding is proposed [24]. This method greatly reduces simulation time while ensuring high modelling accuracy. However, this method still relies on the results of finite element analysis (FEA), and the process of establishing the simulation model is complex, which means that it is neither convenient nor fast enough. Based on the magnetic circuit method, an ideal model of a motor with irregular slot numbers is established in [15]. The model can be conveniently applied in simulation, but accuracy is poor. Due to the influence of poor accuracy, the proposed angle range extension method is only studied on static characteristics. Thus, the first proposal here is a modified model of the LATM with irregular slot numbers. Considering the influence of asymmetrical windings and magnetic flux leakage, the piecewise linearisation method is used to solve the problem of nonlinear torque characteristics, and model accuracy is improved. The operational range extension method is then studied further. The extended angle range selection and constraint conditions are derived when the LATM tracks the sinusoidal position signal, and the dynamic characteristics are analysed by simulation with the modified model. Finally, the LATM tracking experiment is carried out. The results show that the operational range extension method can reduce the volume and mass of the LATM without changing the dynamic characteristics. The new method is of great significance for realising lightness and miniaturisation in aerospace equipment such as oscillating scanning systems.

2 | OPERATIONAL RANGE EXTENSION METHOD

The operational range of LATMs can be extended by reasonably utilising the linear region of the torque-angle characteristic. This method is a new application method of the LATM, hereinafter referred to as the new method. The extended angle range must be selected according to the actual operating condition of the LATM. When the LATM runs the reciprocating motion, the position reference signal is usually a sinusoidal or triangular wave signal. In this section, an LATM following the sinusoidal wave signal is analysed, and the extended angle range is reasonably selected under the corresponding operating conditions.

2.1 | Basic theory of the new method

To simplify the analysis process, the ideal torque-angle characteristic of the LATM is selected for analysis. The ideal torque-angle characteristic is shown in Figure 1. When the rotor is in the constant region, the torque is a constant value. Conversely, when the rotor is in the linear region, the torque changes linearly with the angle. In Figure 1, $\tau$ is the polar distance, $K_{max}$ is the torque coefficient of the LATM in the constant region, $L_s$ is the armature current, $\theta$ is the angle range of the constant region, and $\theta_c$ is the extended angle range. In the conventional method, the LATM operates only in the constant region, while the operational range of the LATM using the new method includes both the constant torque region and the linear region. It is easy to deduce that the wider the constant torque region is, the smaller the motor torque coefficient [15]. For LATMs having the same operating range, the constant torque region of the LATM using the new method is narrower, and thus it has a higher torque density, which results in smaller volume and lighter weight. The operational range of the LATM using the operational range extension method can be expressed as

$$\theta_c = \theta_e + 2\theta_e$$  \hspace{1cm} (1)

To ensure the operation of the motor after using the new method, the output torque in any position within the operational range of the LATM must meet the torque requirement. The torque equation of the LATM is

$$T_{em}(I_0, \alpha) = J\frac{d^2\alpha}{dt^2} + L_s\frac{d\alpha}{dt} + T_{load}$$  \hspace{1cm} (2)

![Figure 1](image.png)  \hspace{1cm} FIGURE 1 Ideal torque-angle characteristic
where $\alpha$ is the rotor position angle of the LATM, $J$ is the moment of inertia, $c_{f}$ is the viscous damping coefficient, and $T_{\text{load}}$ is the load torque.

### 2.2 Selection of extended angle range

The sinusoidal position signal is

$$\alpha(t) = \theta_c + \frac{2\theta_e}{2} \sin(2\pi f t) \tag{3}$$

where $f$ is the frequency of position signal, and $t$ is time. When motor motion is consistent with the position signal, Equation (3) is substituted into Equation (2) to obtain

$$T_{\text{em}}(I_a, \alpha(t)) = -2\pi^2 f^2 (\theta_c + 2\theta_e) J \sin(2\pi f t)$$

$$\quad + \pi f (\theta_c + 2\theta_e) c_{f} \cos(2\pi f t)$$

$$\quad + T_{\text{load}} = T_f + T_{\text{load}} \tag{4}$$

Equation (4) is derived in the form of independent variable $\alpha$:

$$K_T(I_a) = -4\pi^2 f^2 J \alpha + T_{\text{load}}$$

$$\quad + \pi f (\theta_c + 2\theta_e) c_{f} \sqrt{1 - \left(\frac{2\alpha}{\theta_c + 2\theta_e}\right)^2} \tag{5}$$

$$= T_f(\alpha) + T_{\text{load}} + T_{\text{load}}$$

In the LATM motor reciprocating motion process, all kinds of torques change periodically. To ensure the operation of the LATM after using the new method without changing the control method, it is necessary to ensure that

$$K_T(I_a, \alpha) \geq |T_f(\alpha)| + |T_f(\alpha)| + |T_{\text{load}}| \tag{6}$$

where $I_{\text{amax}}$ is the maximum current.

Since the torque characteristic of the motor is symmetric with the 0 position as the center, the torque relation of the half period is as shown in Figure 2.

From Figure 2 and Equation (6), the constraint conditions for extending the angle range can be obtained:

$$\left\{ \begin{array}{l}
\theta_c \leq \frac{K_T I_{\text{amax}} - T_{\text{load}}}{\sqrt{16\pi^4 f^4 J^2 + 4\pi^2 f^2 c_{f}^2}} - \frac{\theta_c}{2} \\
\theta_c \leq \frac{\tau - \theta_c}{\tau - \theta_c - K_T I_{\text{amax}} - T_{\text{load}}} - \frac{\theta_c}{2}
\end{array} \right. \tag{7}$$

After the LATM design is completed, the parameters are known, and the maximum extension angle range can be obtained according to (7). After obtaining the maximum extension angle range, a certain margin can be retained to determine the final operational range of the LATM.

### 2.3 Application example

The specific parameters of the LATM that were selected in this paper are shown in Table 1.

| $T_{\text{max}}$ | 0.043 Nm |
| $2\rho$ | 4 |
| $\alpha_p$ | 0.444 |
| $f$ | 0.5 Hz |
| $I_{\text{max}}$ | 0.12 A |
| $D_{\text{stator}}$ | 72 mm |
| $c_{f}$ | 0.006 N·s·m⁻¹ |
| $L$ | 18 mm |
| $J$ | 0.48 kg·cm² |
| $Z$ | 33 |
| Magnet type | NdFeB |

Abbreviations: $T_{\text{max}}$, maximum torque; $\alpha_p$, pole-pitch coefficient; $Z$, slot number; $2\rho$, pole number; $D_{\text{stator}}$, stator outer diameter; $f$, lamination length.

The cogging torque problem is a main disadvantage of the LATM and affects smooth operation of the motor system. In addition, it is complex to model the LATM when considering the effect of the cogging torque. The cogging torque of the LATM with an irregular slot number is small, as has been studied in reference [15]. Thus, this kind of LATM is selected as the object for application of the new method. The motor model built in

![Figure 2](image_url)
reference [15] has a large deviation from the actual motor. Thus, it must be modified to improve the accuracy of the motor model. The mathematical model of the LATM is similar to that of other motors and is mainly composed of the torque and voltage equations. The difference is that the LATM's electromagnetic torque and induced electromotive force are both functions of angular position. The ideal torque-angle characteristic and induced electromotive force angle characteristic are both trapezoidal waveforms. The motor model established based on this ideal function can be called the ideal mathematical model of the LATM. However, the LATM is affected by many factors such as motor leakage flux, motor saturation and the cogging effect, and the LATM's actual characteristics partially deviate from the ideal mathematical model. The cogging torque of the LATM with an irregular slot number is extremely low and can be considered to have no impact on smooth operation of the motor. Therefore, the influence of the cogging effect is not considered in the modified mathematical model. In addition, without considering the case of motor saturation, only the influence of motor leakage magnetic flux is considered in this section, and functions of the modified torque-angle characteristics and induced electromotive force angle characteristics are derived. Then, the modified mathematical model of the LATM is established based on these functions.

3.1 | Effect of irregular slot number asymmetry structure

It can be easily determined that the ideal electromagnetic torque expression of the LATM is as follows:

$$T_{el}(\alpha, I_a) = k_1(\alpha)B_{sa}Z_aI_a\frac{D_s}{2}$$  

where $\alpha$ is rotor position angle, $Z_a$ is the total number of armature conductors, $I_a$ is armature current, $B_{sa}$ is average magnetic flux density of the air gap, $l$ is the conductor length, $D_s$ is the armature diameter, and $k_1(\alpha)$ is the coupling coefficient representing the coupling relationship between permanent magnet and stator winding:

$$k_1(\alpha) = \begin{cases} \frac{\tau + 2\alpha}{\tau} & \alpha \in \left(\frac{-\tau}{2}, \frac{-\tau - b_p}{2}\right) \\ \frac{b_p}{\tau} & \alpha \in \left[-\frac{\tau - b_p}{2}, \frac{\tau - b_p}{2}\right] \\ \frac{\tau - 2\alpha}{\tau} & \alpha \in \left(-\frac{\tau}{2}, +\frac{\tau}{2}\right) \end{cases}$$

where $b_p$ is magnetic pole width.

Because of the irregular slot number structure, the winding is asymmetric in space. When the rotor is in a certain position, the coupling condition between each magnetic pole and stator winding is not always the same. Therefore, the specific coupling condition of each pole must be analysed. The average value of the coupling coefficient is

$$k_1'(\alpha) = \begin{cases} \sum_{k=1}^{2p} k_1(\alpha + (k - p)\alpha_t - t(k)) & \alpha < 0 \\ \sum_{k=1}^{2p} k_1(\alpha - (k - p)\alpha_t + t(k)) & \alpha \geq 0 \end{cases}$$

(10)

$$\alpha_t = \tau - Z_c t$$

(11)

where $Z_c$ is the number of stator slots contained in a stator phase belt, $t$ is stator tooth pitch, and $t(k)$ represents the influence of empty slots.

The value of $t(k)$ is determined by the number and distribution of empty slots. For the LATM with an irregular number of slots, when there is only one empty slot in the motor, the cogging torque fluctuation is small and material utilization is at its highest rate. With the increase in the number of empty slots, the utilization rate of the motor material decreases, but the torque fluctuation of the slot may not be improved. Therefore, only the LATM structure with one empty slot is discussed.

The phase belt distribution of a 33-slot four-pole LATM is shown in Figure 3. When $\alpha$ is less than 0, the phase belt is numbered clockwise as a red number. When $\alpha$ is greater than 0, the phase bands are numbered counterclockwise with a black number. As shown in the figure, the motor is always affected by the half-empty slot in the last phase belt according to the numbering sequence. Thus, in the LATM with one empty slot,

$$t(k) = \begin{cases} 0 & k \neq 2p \\ \frac{t}{2} & k = 2p \end{cases}$$

(12)

3.2 | Effect of motor leakage flux

Since the formulas derived above are based on air gap average flux density, the influences of winding end leakage flux and leakage flux between adjacent poles have been
excluded. Only leakage flux between adjacent stator teeth affects the ideal characteristics of the LATM. As can be seen from Figure 4, when the rotor is close to the junction position of the stator winding phase belt, due to the existence of stator teeth, the air gap magnetic field that is only coupled with the forward winding, in theory, also has a small amount of coupling with the reverse winding. This is the main reason that nonlinear torque exhibits a decreasing trend when the rotor is near the boundary position of the constant region. The phenomenon of unexpected coupling between the magnetic field and other phase belts when the rotor is in a specific position is defined as magnetic leakage between phases. When the rotor is in the position shown in Figure 4, magnetic leakage between phases and between stator teeth can lead to reductions in motor torque. Therefore, the reverse torque caused by leakage flux should be subtracted from ideal torque. The stator teeth near the junction of the phase belt are analysed. Leakage flux is considered generated by the magnetic pole within the tooth distance range, and the magnetic induction intensity generated is related to the magnetic pole angle in the range. The magnetic pole angle that produces leakage flux is

\[
g(\alpha) = \begin{cases} 
0 & \alpha \in \left[ -\frac{\tau}{2}, \frac{\tau}{2} \right] \\
t + \alpha - \frac{b_p}{2} & \alpha \in \left( \frac{b_p - \tau}{2}, \frac{b_p - \tau - 2\ell}{2} \right) \\
-t + \alpha - \frac{b_p}{2} & \alpha \in \left( \frac{-b_p - \tau}{2}, \frac{-b_p - \tau - 2\ell}{2} \right) \\
-t - \alpha - \frac{b_p}{2} & \alpha \in \left( \frac{-b_p + \tau}{2}, \frac{-b_p + \tau + 2\ell}{2} \right) \\
t + \alpha + \frac{b_p}{2} & \alpha \in \left( \frac{b_p + \tau}{2}, \frac{b_p + \tau + 2\ell}{2} \right) \\
-t + \alpha + \frac{b_p}{2} & \alpha \in \left( \frac{-b_p + \tau}{2}, \frac{-b_p + \tau + 2\ell}{2} \right) \\
0 & \alpha \in \left[ -\frac{\tau}{2}, \frac{\tau}{2} \right]
\end{cases}
\]

(13)

Considering the asymmetric structure of the irregular slot number, the formula of electromagnetic torque affected by magnetic flux leakage is arranged into a common format for structures with a regular slot number and an irregular slot number:

\[
T_{\omega}(\alpha) = \left( 1 - \frac{D_s \sum_{k=1}^{2p} f(\alpha)}{8k_{\text{max}} b_1 Z_p p^2} \right) k_l(\alpha) B_0 I_d D_s \frac{D_s}{2}
\]

(14)

\[
f(\alpha) = \begin{cases} 
g(\alpha - (k - 1)\alpha) & \alpha \leq 0 \\
g(\alpha + (k - 1)\alpha) & \alpha > 0
\end{cases}
\]

(15)

where \( b_1 \) is the angle of tooth width, and \( k_{\text{max}} \) is the maximum value of \( k_l(\alpha) \).

The leakage flux coefficient can be obtained from Equation (14):

\[
k_l(\alpha) = \left( 1 - \frac{D_s \sum_{k=1}^{2p} f(\alpha)}{8k_{\text{max}} b_1 Z_p p^2} \right)
\]

(16)

### 3.3 Modified model

Considering the above effects, Equation (8) is modified as

\[
T_{\omega}(\alpha, I_d) = k_l(\alpha) \cdot k_p(\alpha) B_0 I_d Z_p D_s \frac{D_s}{2}
\]

(17)

The torque coefficient is

\[
K_{T2}(\alpha) = k_l(\alpha) \cdot k_p(\alpha) B_0 I_d Z_p D_s \frac{D_s}{2}
\]

(18)

By Equation (17), the torque-angle characteristic of a 33-slot four-pole LATM is shown in Figure 5. It can be seen from Figure 5 that the modified torque-angle characteristic is consistent with the FEA and experimental results. The error analysis of the FEA results and the modified model is shown in Figure 6. It can be seen from Figure 6 that the error of the modified model is small in the constant region and mainly caused by the cogging effect. In the linear region, the larger the angle is, the greater the error, but it is still within the 3% range, which is acceptable. The comparison results can verify the correctness of the derived equations and ensure the accuracy of the modified mathematical model based on the torque-angle characteristic.

Due to the relationship between the torque and the induced electromotive force of the LATMs, the modified equations of induced electromotive force can be easily obtained:

\[
E_{\omega}(\alpha, \omega) = K_{T2}(\alpha) \cdot \omega
\]

(19)
where $\omega$ is angular velocity of the rotor.

In the dynamic simulation analysis of the motor, the improved model can be used to conveniently and quickly establish the simulation model and greatly improve the speed of the simulation calculation.

According to Equations (17) and (19), the voltage and mechanical equations of the LATM, the modified mathematical model of the LATM can be obtained as shown in Figure 7.

4 | SIMULATION AND EXPERIMENTAL VERIFICATIONS

4.1 | Simulation analysis

Based on the modified mathematical model of the LATM, a three-closed-loop simulation model of tracking characteristics is established, as shown in Figure 8. The new simulation model takes 6 s to analyse the two motion periods of the LATM, while the simulation model based on the 2-D FEA model takes at least 2 h.

The design parameters of the LATM operating with the operational range extension method are different from those for the LATM operating with the conventional method. The parameters of the conventional-method LATM and new-method LATM are put into the simulation model for simulation analysis of tracking characteristics. The tracking characteristics and current waveforms obtained by simulation are shown in Figures 9 and 10. It can be seen that the current amplitude of the two motors is the same under the same load. However, the load capacity of the new-method motor is reduced in the extended range, and the current must increase accordingly, which results in a larger RMS current.

The tracking characteristics of the two motors are the same, but the current waveforms are slightly different. The specific parameter comparison is shown in Table 2. It should
be noted that the two motors have the same outer diameter, while the conventional-method LATM's axial length must be longer to achieve the same performance parameters.

As can be seen from the table, the performance of the two LATMs is basically the same, but the weight of the new-method LATM is reduced by 7.6%, and the volume is reduced by 10%. The results show that the torque density of the LATM can be effectively increased using the operational range extension method, which is consistent with the theory in Section 2.

4.2 | Experiment

The LATM experiment using the operational range extension is conducted. The prototype and corresponding test frame are shown in Figure 11. The parameters of the prototype are the same as those of the new-method LATM in Table 2. The tracking characteristics are shown in Figure 12. It can be seen from Figure 12 that the LATM using the operational range extension method has good tracking characteristics. The error is relatively large near the extended range, while the error between the reference signal and measured results is no more than 2.5°. The feasibility of the operational range extension method is verified.

The experimental current waveform is shown in Figure 13. Compared with the simulation waveform, the experimental current waveform has a certain degree of harmonics affected by factors such as cogging torque. The accuracy of the simulation model is verified by the results of the current waveform.

4.3 | Error analysis

The simulation results in Figure 13 are obtained under the condition of ideal assembly accuracy, and the effect of cogging torque can be ignored. However, the actual LATM has cogging torque because of poor mechanical assembly accuracy. The
eccentric distance is defined as \( s \). Figure 14 shows the relationship between cogging torque and \( s \). The measured cogging torque of the prototype is similar to the FEA result of \( s = 0.03 \) mm. Therefore, the experimental error is judged to be caused by the eccentricity of the rotor, and the eccentric distance is about 0.03 mm. The measured eccentric distance of the rotor is 0.025 mm, which verifies the judgement above. It should be noted that the irregular slot number structure leads to unbalanced magnetic tension between the rotor and stator. Hence, the problem of eccentricity is difficult to improve completely. The error can be reduced to be within an acceptable range by improving the machining and assembly accuracy of the LATM. As shown in Figure 12, although the current has harmonic errors, the position tracking characteristic is still good, which is acceptable.

5 Conclusion

In this paper, a theoretical analysis, simulation and experimental verification of the operational range extension method have been presented for improving the power density of an LATM with irregular slot numbers. The following conclusions can be drawn from the results:

1. The extended angle range selection theory and constraint conditions of LATM sinusoidal tracking have been derived based on the theoretical analysis. This theory reveals the relationship between the sinusoidal tracking characteristic and leading parameters, providing a reference for application of the new method.

2. The modified model of the irregular slot number LATM has been established to achieve a more accurate simulation. Within the operational range, the error of the improved model is within 2% compared with that of the finite element model. By the modified model, the simulation time is greatly reduced, which makes dynamic analysis of the LATM more convenient.

3. Simulation and experimental verification of the operational range extension method have been carried out. The results show that the weight of the LATM using the new method is reduced by 7.6%, and the volume is reduced by 10%, compared with the conventional LATM. Thus, the operational range extension method is effective for improving LATM power density.

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ORCID
Pengcheng Ma https://orcid.org/0000-0003-1050-7422

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