Design of the extruder drive motor and its HNTSM speed control with disturbance observer

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Abstract. In order to meet the requirements of 25kW rated power and 1500r/min rated speed required by the extrusion process of polyester fiber composite materials, a PMSM suitable for this working condition was designed to complete the driving task of the extruder. The geometric model of the motor was established using RMxprt, and the load operation state of the motor was simulated by Maxwell. The motor speed was controlled by a HNTSM control scheme with a disturbance observer, and based on Twin builder and simulink coupled simulation. The simulation results show that the motor can reach the required rated power and rated speed. HNTSM control with disturbance observer is more robust than HNTSM and PID control, and can suppress the jitter caused by sliding mode control. However, compared with PID control, there is still some jitter.

1. Introduction
Polyester fiber composite materials can well increase the strength and hardness of the material [1]. During extrusion, the surface of the glass fiber will produce a liquid film with the same speed as its surface. It is easy to move relative to the liquid phase during mixing. The flow rate of the liquid film on the surface is different from that of the liquid phase, which creates frictional resistance and causes the liquid phase flow rate to fluctuate. So that the screw load fluctuates greatly [2], so the drive motor needs to have good robustness.

In terms of motor design, permanent magnet synchronous motors are developing in the direction of high speed, high torque, high power, and miniaturization. However, due to different design requirements, the different designer will use different design methods [3], and LIU X is equal to a series of PMSM parameters determined through experiments in 2016 [4]. M P Ciurys designed an inner rotor brushless DC motor in 2017, and adopted the PWM control method. At the same time, the motor circuit was studied using Maxwell software [5]. In 2014, Li Haibo used Maxwell and simplorer Co-simulation to design the motor which can verify the feasibility of motor design [6].

In terms of motor control methods, sliding mode control has switching characteristics, which can make the system move up and down with a small amplitude and high frequency under certain conditions along the designed state. This movement is not sensitive to external disturbances and parameter changes, so the system is robust [7], Zhao Yue established a variable structure controller based on sliding mode for vector control of PMSM in 2016. Although it has a certain robustness, the inherent jitter of sliding mode control is not eliminated [8]. Ke Shaoxing has studied the speed control strategy based on sliding mode observer in 2020, which has further enhanced the robustness [9]. B Xu et al [10] designed an adaptive variable exponential approach rate. Through the first-order norm of the system state, the constant velocity term and the exponential term were adaptively adjusted to reduce chattering to a certain
extent. Y Wang et al [11] proposed a new approach rate based on system state variables and power term of sliding mode function, which effectively suppresses the inherent chattering problem of the control system. Chen Siyi et al [12] designed a disturbance observer to compensate on the basis of sliding mode control to weaken the system jitter problem. FNAIECH MA and others apply fuzzy inference and sliding mode control to the fault tolerance of six-phase induction motor winding phase failure, which improves the robustness and position tracking accuracy of the system, but it has the defects of difficult to determine fuzzy parameters and high frequency switching of sliding mode gain [13].

In order to solve the problem of the robustness of the drive motor, a motor that meets the working environment requirements of this extruder is designed. This paper uses RMxprt to carry on the electrical machinery modeling, and imports Maxwell to carry on the simulation, obtains the output power and the rotational speed. Then the HNTSM controller with disturbance observer is designed to meet the robustness requirements and reduce jitter, and the twin builder and simulink co-simulation is used to obtain the speed response.

2. The mathematical model of PMSM
The three-phase winding axis ABC constitutes the three-phase shaft system, the stator voltage vector equation is:

$$u_s = R_s i_s + \frac{d}{dt} (L_s i_s) + \frac{d}{dt} (\psi_f e^{j\beta})$$

(1)

In the formula, $u_s$ is the stator voltage space vector, $R_s$ is the stator phase resistance, $i_s$ is the current space vector, $L_s$ is the equivalent synchronous inductance, $\psi_f$ is the excitation flux linkage space vector, and $e^{j\beta}$ is the transformation factor. The flux linkage equation is:

$$\psi_s = L_s i_s + \psi_f$$

(2)

In the formula, $\psi_s$ is the stator flux space vector. The motion equation of the motor is:

$$J \frac{d\omega_m}{dt} = T_e - T_L$$

(3)

In the formula, $J$ is the moment of inertia, $\omega_m$ is the angular velocity of the motor, $T_e$ is the motor torque, and $T_L$ is the load torque. Performing Clark transformation and Park transformation on the description of the ABC coordinate system of the three-phase mathematical model can decouple the coupling relationship between the variables to make the control simpler and help design an effective controller. The mathematical model described under the two-phase rotating MT shaft system obtained after transformation is as follows. The flux equation of the motor is:

$$\psi_q = L_q i_q$$

(4)

In the formula, $\psi_q$ is the q-axis stator flux linkage, $L_q$ is the q-axis stator self-inductance, and $i_q$ is the q-axis current.

$$\psi_d = L_d i_d + \psi_f$$

(5)

In the formula, $\psi_d$ is the d-axis stator flux linkage, $L_d$ is the d-axis stator self-inductance, and $i_d$ is the d-axis current.

3. Design of extruder drive motor
Designing a drive motor that meets the electromagnetic torque required by the extruder must meet the electromagnetic torque formula [14]:

$$T_e = p_n \left[ \psi_q i_q \sin \beta + \frac{1}{2} (L_d - L_q) i_d^2 \sin 2\beta \right]$$

(6)

In the formula, $p_n$ is the number of pole pairs, and $\beta$ is the torque angle, which is the space between the stator three-phase fundamental wave composite magnetomotive force axis and the permanent magnet fundamental excitation magnetic field axis Electrical angle. among them, $\psi_f = \frac{\sqrt{2}}{\omega_e} E_0$. Where $\omega_e$ is the electrical angular velocity, which is related to the working conditions, and $E_0$ is the no-load electromotive force induced in the winding by the permanent magnet excitation field, and $E_0 = -L \frac{di}{dt}$. Obviously, the higher the number of pole pairs, the greater the torque, but the larger the motor volume,
the greater the moment of inertia. Through debugging, the parameters of PMSM finally designed are as table 1.

| Parameter          | Value     |
|--------------------|-----------|
| Stator Outer Diameter | 260mm    |
| Stator Inner Diameter | 140mm    |
| Rotor Outer Diameter | 139.6mm  |
| Rotor Inner Diameter | 60mm     |
| Length             | 90mm     |
| Rated Power        | 25KW     |
| Rated Speed        | 1500rpm  |
| Number of Poles    | 6        |
| Winding Layers     | 2        |
| Parallel Branches  | 3        |
| Conduction per Slot | 50       |
| Magnet Thickness   | 12mm     |

Motor 2D model and 3D model and characteristic curve are shown in figure 1 and figure 2. It can be seen from the figure that it meets the design requirements.

4. Design of HNTSM controller

This article adopts HNTSM control strategy to realize PMSM angular velocity control.

4.1. Design of Sliding surface

Define the state variables of the system as:

\[
\begin{align*}
    x_1 &= \omega_m^* - \omega_m \\
    x_2 &= \dot{\omega}_m
\end{align*}
\] (7)
In the formula, $\omega_m$ and $\omega_m$ are the set speed of the motor and the actual speed of the motor respectively. Therefore, the derivative of the state variable can be obtained:

\[
\begin{align*}
X_1 &= x_2 \\
X_2 &= \omega_m = \frac{(T_e - T_L)}{J}
\end{align*}
\]

Based on NTSM, the sliding surface of the HNTSM is designed as:

\[
s(x) = x_1 + cx_2 + rx_2^p \frac{1}{q} = 0
\]

Where, 
\[
c = \begin{cases} 
\alpha, & |x_1| \geq 1 \\
0, & |x_1| < 1
\end{cases}
\]

Among them, $\alpha > 0$, $\beta > 0$, $p$ and $q$ are both odd numbers, and $q < p < 2q$.

HNTSM is composed of LSM and NTSM. When the state point is farther away from the sliding surface, that is, the larger $|x_1|$ is, and is greater than or equal to 1, the smaller the effect of NTSM, the greater the effect of LSM, and the greater the distance between the state point and the sliding surface. The faster the convergence speed is when the distance is far; at the same time, when the state point is closer to the sliding mode surface, that is, $|x_1|$ is smaller and less than 1, the LSM effect is smaller, and the NTSM effect is greater, so that the system converges quickly globally.

### 4.2. Solution of control law

Choose reaching law, $\dot{s}(x) = -asgn(s) - bs$, Where: $a > 0$; $b > 0$. When $s(x) > 0$, the above formula is simplified to:

\[
\frac{ds(x)}{dt} = -a - bs
\]

Solutions have to:

\[
s(x) = -a + \left( s_0 + \frac{a}{b} \right) e^{-bt}
\]

Obviously, the approaching movement of the system state point is mainly affected by $b$. The larger the $b$, the faster the approaching speed. But when the state point approaches $s(x) = 0$, the approach speed is close to 0. At this time, the larger $a$ is, the faster the state point moves to the sliding surface, but the greater the switching lag, the greater the jitter, so Appropriate anti-shake measures need to be adopted. The output of the controller at this time is:

\[
i_q = \frac{1}{1.5Pn\psi f} \int_0^t \left[ \frac{x_2}{c^2 + p q x_2^p q^{-1}} + asgn(s) + bs \right] dt
\]

### 4.3. Stability analysis

Take the Lyapunov function as:

\[
V(x) = \frac{1}{2}s^2
\]

which is:

\[
\dot{V}(x) = s\dot{s} = \left( c + P q x_2^p q^{-1} \right) \left( -asgn(s) - bs \right) \leq \left( c + P q x_2^p q^{-1} \right) \left( -a|s| - bs \right) \leq 0
\]

Obviously, only when $x_1 = 0$, $V(x) = 0$. According to the Lyapunov stability theory, it can be known that the state variables of the system can all move to the sliding mode surface within a finite time, and the sliding mode movement is stable [15].

### 5. HNTSM with disturbance observer

When the system is disturbed, or there may be a short-term impact, a larger value of $a$ needs to be selected to ensure that the control system provides enough given current $i_q$ to suppress the fluctuation of the motor speed. But obviously, the larger $a$ is, the greater the jitter of the speed is, and therefore a tiny oscillation is produced. In order to suppress this oscillation and at the same time suppress the disturbance caused by the outside world, a disturbance observer is introduced on the basis of non-singular terminal sliding mode control, and the current is fed forward compensation to improve the robustness of the system.
5.1. Design of disturbance observer

Rewrite formula (3) as:
\[
\frac{d \hat{\omega}_m}{dt} = \frac{1.5 P_n \psi f}{J} - \frac{g(t)}{J}
\] (15)

Where:
\[
g(t) = T_L - J \Delta a - J \Delta b
\]

The motor state space can be expressed as:
\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{bmatrix} =
\begin{bmatrix}
0 & -1/J \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} + 
\begin{bmatrix}
1/J \\
0
\end{bmatrix} u;
C = [1 0].
\]

Obviously, the observability matrix \(N\) of the state space is:
\[
N = \begin{bmatrix}
C \\
CA
\end{bmatrix} =
\begin{bmatrix}
1 & 0 \\
0 & -1/J
\end{bmatrix}
\]

Obviously, \(N\) is a full-rank matrix, and the system is fully observable, so the disturbance observer exists. Therefore, the disturbance observer can be constructed as follows:
\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{bmatrix} = A \begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{bmatrix} + 
\begin{bmatrix}
1/J \\
0
\end{bmatrix} u + G \left( \begin{bmatrix}
y \\
\hat{y}
\end{bmatrix} - 
\begin{bmatrix}
y \\
\hat{y}
\end{bmatrix}\right)
\]

Where,
\[
\begin{bmatrix}
\omega_m \\
g(t)
\end{bmatrix} \text{ is the observed value of } x; \quad \begin{bmatrix}
y \\
\hat{y}
\end{bmatrix} \text{ is the observed value of } y; \quad G = [g_1, g_2] \text{ is the feedback matrix. Therefore, the structure diagram of the disturbance observer system can be represented as shown in the figure 3.}
\]

5.2. Stability analysis of disturbance observer

The observer error equation is:
\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{bmatrix} = (A-GC) \begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{bmatrix}
\]

Where: \(\hat{x} = x - \hat{x}\) is the error value of \(x\), then have:
\[
(A-GC) = \begin{bmatrix}
-g_1 & -1/J \\
g_2 & 0
\end{bmatrix}
\]

Therefore, the characteristic equation of \(A-GC\) is:
\[
\det \left( sI - \begin{bmatrix}
-g_1 & -1/J \\
g_2 & 0
\end{bmatrix}\right) = 0
\]

which is:
\[
s^2 + g_1 s + \frac{g_2}{J} = 0
\]

Assuming that the equation has two roots \(\alpha_1\) and \(\alpha_2\), and satisfies \(\alpha_1 = \alpha_2 < 0\), after entering the above formula, we get:
\[
s^2 - 2\alpha_1 s + \alpha_1^2 = 0
\]

Obviously:
\[
\begin{cases}
g_1 = -2\alpha_1 \\
g_2 = J\alpha_1^2
\end{cases}
\]

Therefore, choosing \(g_1 > 0\) and \(g_2 < 0\) can make the disturbance observer error approach zero. Obviously, \(|g_1|\) and \(|g_2|\) determine the distance between the pole of the observer and the imaginary axis,
Therefore, adjusting \( g_1 \) and \( g_2 \) can make the system achieve a better balance between stability and convergence speed, which can improve the effect of the observer.

5.3. Design of HNTSM with disturbance observer

Feed forward compensation of the output of the observer to the current, and get:

\[
i_q^* = \frac{J}{1.5P_{rms}^2} \int_0^t \left[ \frac{1}{s^2} \frac{1}{s^2} x_2 + \text{sgn}(s) + bs \right] dt + kG(t)
\]

Where \( i_q^* \) is the given current, \( k \) is the feedforward gain of the disturbance observer. When the feedforward compensation of the disturbance is introduced into the given current, the speed fluctuation caused by the external disturbance can be further reduced, and the jitter caused by the system itself can be weakened. The control system of HNTSM with disturbance observer is in figure 4.

6. Simulation and comparative analysis

The simulation model of Twin Builder and Simulink co-simulation based on the HNTSM controller with disturbance observer is shown in Figure 5.

This paper uses ANSYS Electronics to design a specific motor suitable for extruders. Simulink is a professional control system simulation software, so this paper designs a non-singular terminal sliding mode control system for motors that introduces an error feedback observer based on the Simulink platform. In order to simulate and verify the control effect of the motor, the motor model in the Simulink
component library can no longer meet the requirements of reflecting the performance of the motor designed this time. Therefore, it is necessary to adopt the Twin Builder module in ANSYS Electronics to establish a model based on Twin Builder and Simulink. Joint simulation to realize the simulation verification of the motor output speed.

As shown in figure 6, figure 7, figure 8. At 0.3 second, a positive 100r/min disturbance is added to the rotation speed. It can be seen from the simulation results that the introduction of disturbance observer control system has good robustness, and the maximum disturbance reaches 1600r/min at 0.3001 second. After 0.3005 second, the speed returns to 1500r/min, the adjustment time is 40% shorter than the PID control scheme, and the jitter is 20% smaller than HNTSM. It can be seen that the control system has strong robustness and little jitter. It meets the design requirements, but is still 10% larger than the jitter of the PID control scheme, so there is still room for improvement.

7. Conclusion
This paper designs a motor suitable for extruder. The RMxprt simulation results show that the motor can meet the required torque and speed requirements. In order to ensure that the output speed of the motor is controllable and has high robustness, this paper designs a HNTSM controller that introduces a disturbance observer.
The joint simulation results based on Twin Builder and Simulink show that the interference-introducing HNTSM control scheme used in this experiment is more robust than the traditional PID, and the recovery speed is reduced by about 40%, and at the same time, its jitter is 20% less than HNTSM control, but its jitter is still 10% larger than PID control. The reason why the jitter is greater than PID control is that the parameter adjustment is not optimized enough, and the jitter suppression ability brought by sliding mode control is insufficient. In the follow-up research, we can try to use neural network method to optimize the parameters to further improve the control effect of the controller.

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