

Gaussian Dynamic Gain Sliding Mode Position Control of Flexible Servo Systems

Zhichen Lin, Chendong Zhang, Zhiqiang Wang, *Member, IEEE*, and Tingna Shi, *Senior Member, IEEE*

Abstract—In the position control of a flexible servo system (FSS), the use of sliding mode control (SMC) with a fixed constant sliding surface leads to overshoot in the step position response. This paper first clarifies through analysis that the acceleration error and jerk error in the constant-coefficient sliding surface are the core causes of this overshoot phenomenon, both of which will generate accelerating current during deceleration. To address this issue, a Gaussian dynamic gain sliding mode control (GDG-SMC) strategy is proposed. By designing a sliding surface with GDG, the proposed strategy increases the proportion of the velocity error and the reaching law component in the q -axis current during deceleration, thereby generating braking current to suppress overshoot. Coupled with an anti-windup super-twisting reaching law to mitigate the overshoot potentially induced by the integral term, the proposed method can further reduce the position response error and realize fast overshoot-free position tracking. Comparative experimental results verify the feasibility of the proposed method.

Index Terms—Adaptive control, Flexible servo system (FSS), Overshoot suppression, Position control, Sliding mode control (SMC).

I. INTRODUCTION

WITH the rapid development of robot control technology, robots have gradually expanded from traditional industrial fields to scenarios requiring extensive human-robot interaction [1]-[2]. Compared with rigid robots, flexible robots feature the advantages of compact size, light weight, and high interaction safety, making them the preferred solution in the field of human-robot interaction [3]. As a

critical actuation unit of flexible robots [4]-[5], the effective and high-precision control of the flexible servo system (FSS) has become a prominent research hotspot at present.

The introduction of flexible components (e.g., springs) increases the difficulty of its position control. To achieve precise and stable position control, researchers have applied various control algorithms to the position control of FSSs, including sliding mode variable structure control [6]-[8], active disturbance rejection control [9]-[10], model predictive control [11]-[12], and neural network control [13]-[14]. Among these algorithms, sliding mode variable structure control, as a highly robust control algorithm with low model dependence and strong anti-disturbance capability [15], has been widely applied in motor control and robot joint control [16]-[19].

Although traditional sliding mode control (TSMC) has strong robustness in the position control of FSSs, it still faces two major challenges. First, the impact of mismatched disturbances (such as external random disturbances, parametric uncertainties, and unmodeled dynamics) on high-precision positioning has not been effectively eliminated [20]. Second, it suffers from inherent drawbacks, including control chattering and excessive time consumption in the reaching phase. To address the above deficiencies, the existing improved strategies can be mainly summarized into the following four categories:

1) Disturbance observer-based compensation methods

By constructing a disturbance observer to realize online estimation and feedforward compensation of mismatched disturbances, the impact of such disturbances on the steady-state accuracy of the system is reduced. Typical schemes include incorporating mismatched disturbance terms into state variables and designing a second-order disturbance observer [21]; developing high-order sliding mode observers for disturbances on the motor side and load side respectively [22]; constructing a generalized disturbance observer to improve the position tracking accuracy under unknown disturbances [23].

2) Sliding mode surface structure improvement methods

The convergence performance and transient response of the system are improved by reconstructing the form of the sliding mode surface. Typical examples include adopting a terminal sliding mode surface to achieve finite-time stability [22]; designing a nonsingular fixed-time sliding mode surface to ensure the convergence of system states within a fixed time [23]; designing a composite sliding mode surface to ensure

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Zhichen Lin is with the Zhejiang University Advanced Electrical Equipment Innovation Center, Hangzhou 311107, China (e-mail: linzhichen@zju.edu.cn).

Chendong Zhang and Tingna Shi are with the College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China (e-mail: 22310038@zju.edu.cn; tmsi@zju.edu.cn).

Zhiqiang Wang is with the Zhejiang University Advanced Electrical Equipment Innovation Center, Hangzhou 311107, China, and also with the School of Electrical Engineering, Tiangong University, Tianjin 300387, China (e-mail: wangzhiqiang@tiangong.edu.cn).

(Corresponding author: Zhichen Lin)

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that the error converges within a fixed time independent of initial conditions [24]-[25]; introducing a global sliding mode surface to make the initial state of the system directly lie on the sliding mode surface, which completely eliminates the reaching phase [26].

3) Reaching law optimization and chattering suppression methods

To attenuate the high-frequency chattering of sliding mode control (SMC), existing studies have optimized the switching function of the reaching law and introduced fuzzy control to realize the adaptive adjustment of reaching law parameters [27], which effectively smooths the control signal while maintaining the robustness of the system. Furthermore, on the basis of optimizing the switching function of the reaching law, the control gains are updated online via an adaptive mechanism to cope with unknown disturbance bounds [28].

4) Intelligent learning and parameter adaptive methods

Some studies have integrated intelligent algorithms into the sliding mode framework. For example, a radial basis function neural network (RBFNN) is adopted to perform online correction of the offline-identified friction model, so as to improve the compensation accuracy under uncertain environments [23], and parameter identification is adopted to compensate for fast-varying mechanical parameters in real time for system parameter adaptation [29].

However, current research on sliding mode position control for FSS mainly focuses on improving steady-state accuracy and suppressing chattering, while insufficient attention has been paid to the overshoot problem in the transient process. The experimental waveforms of point-to-point positioning in related works show that overshoot commonly exists in the position response. Nevertheless, overshoot is unacceptable in application scenarios where obstacles or position constraints exist near the target point. Therefore, this paper focuses on the effective suppression of position overshoot in sliding mode position control of FSS.

The motivation of this study is to solve the transient overshoot problem of SMC-based FSS position control in point-to-point positioning, where the target point may be close to mechanical constraints, obstacles, or fragile objects. In such scenarios, reducing only the steady-state error is insufficient, and the deceleration-stage current distribution must be redesigned to avoid crossing the target position.

The analysis in this paper shows that the introduction of the elastic torsion spring increases the dynamic order of the system, making it necessary to introduce high-order differential terms such as acceleration error and jerk error into the sliding mode surface design. These terms will generate additional acceleration current in the deceleration phase, which is the main cause of position overshoot. The widely used constant-coefficient sliding mode surface is difficult to effectively suppress this current under different positioning commands, which further affects the deceleration process and eventually induces overshoot.

To address the above problems, this paper proposes a Gaussian dynamic gain-SMC (GDG-SMC) strategy for position control. First, a GDG sliding mode surface is

proposed, where the constant coefficients of the sliding mode surface are replaced by Gaussian functions related to the position error. This sliding mode surface can effectively reduce the acceleration current in the deceleration phase, thereby effectively suppressing chattering. Second, the super-twisting reaching law is optimized, and an anti-integral saturation super-twisting reaching law is proposed, which suppresses the position overshoot that may be caused by the integral term in the super-twisting algorithm based on reducing chattering. Finally, a lumped disturbance decoupling observer is designed with reference to [30] to observe the lumped disturbances on the motor side and the load side. The observed lumped disturbance values are fed back to the sliding mode controller to enhance the position control performance of the system under mismatched disturbances.

The rest of this paper is organized as follows. Section II establishes the dynamic model of the series elastic actuator system with lumped disturbance terms. Section III analyzes the limitations of the traditional sliding mode position control strategy. Section IV proposes the GDG-SMC strategy, including the design of the GDG sliding mode surface, the anti-integral saturation super-twisting reaching law, and the lumped disturbance decoupling observer. Section V presents the stability analysis of the proposed strategy. Section VI carries out the experimental verification. Section VII summarizes the full text.

II. DYNAMIC MODELING OF FSSs CONSIDERING LUMPED DISTURBANCE TERMS

The FSS is mainly composed of a permanent magnet synchronous motor (PMSM), a high-reduction-ratio reducer, and an elastic torsion spring, as shown in Fig. 1. The high-reduction-ratio reducer achieves torque amplification and high-precision transmission. As the core flexible component, the elastic torsion spring not only improves the safety and interaction compliance of the system, but also enhances its impact resistance and transient force output performance. In the figure, θ_M , ω_M , J_M , B_M , and T_M represent the position, rotational speed, moment of inertia, friction coefficient, and electromagnetic torque on the PMSM side, respectively; θ_L , ω_L , J_L , B_L , and T_L represent the position, rotational speed,

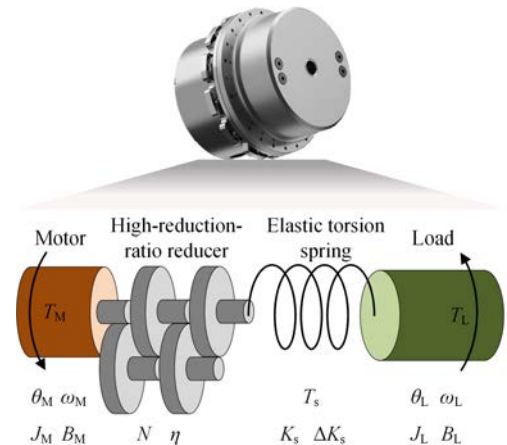


Fig. 1. Mechanical structure of the FSS.

moment of inertia, friction coefficient, and load torque on the load side, respectively. N and η stand for the reduction ratio and transmission efficiency of the reducer, respectively; K_s and ΔK_s are the nominal value of the stiffness of the elastic torsion spring and its error from the actual value, respectively. T_s is the transmission torque, whose magnitude is proportional to the position difference between the two sides of the elastic torsion spring.

The ratio of the rotational speeds on both sides of the reducer is strictly equal to the reduction ratio N and remains constant regardless of operating conditions, while the ratio of the torques on both sides varies with operating conditions. In addition, due to factors such as measurement errors and component aging, the actual stiffness of the elastic torsion spring usually deviates from its nominal value. Based on the above considerations, this paper establishes a dynamic model of the series elastic actuation system that takes into account the variation of the reducer transmission efficiency and the stiffness mismatch of the elastic torsion spring in the control system, that is:

$$\begin{cases} J_M \dot{\omega}_M = K_t I_q - T_{M-lump} \\ T_{M-lump} = \frac{T_s}{N\eta} + B_M \omega_M \end{cases} \quad (1)$$

$$T_s = K_s \left(\frac{\theta_M}{N} - \theta_L \right) - \Delta K_s \left(\frac{\theta_M}{N} - \theta_L \right) \quad (2)$$

$$\begin{cases} J_L \dot{\omega}_L = K_s \left(\frac{\theta_M}{N} - \theta_L \right) - T_{L-lump} \\ T_{L-lump} = \Delta K_s \left(\frac{\theta_M}{N} - \theta_L \right) + T_L + B_L \omega_L \end{cases} \quad (3)$$

Among these parameters, I_q denotes the q-axis current of the motor; K_t represents the motor torque constant, and the product $I_q K_t$ yields the electromagnetic torque T_M of the motor. T_{M-lump} and T_{L-lump} are the lumped disturbance torques on the motor side and the load side, respectively.

FSS is generally equipped with encoders on both the motor side and the load side, which can measure θ_M , ω_M , θ_L , and ω_L in the model, respectively. J_M and J_L can be identified offline through simple acceleration and deceleration experiments. In contrast, T_{M-lump} and T_{L-lump} require a dedicated torque observer to realize real-time observation of the lumped disturbance torques.

Assumption 1: The motor-side and load-side positions/speeds are measurable or can be obtained from encoders with bounded measurement noise.

Assumption 2: The equivalent inertias and nominal stiffness used in the controller are positive and bounded, while the efficiency variation, stiffness mismatch, friction, and load torque are regarded as bounded lumped disturbances.

Remark 1: Assumption 1 ensures the availability of feedback signals; Assumption 2 provides the boundedness condition required for disturbance observation and sliding-mode robustness.

III. ANALYSIS ON LIMITATIONS OF TRADITIONAL SLIDING MODE POSITION CONTROL STRATEGIES

The overall block diagram of the sliding mode position control strategy for the FSS is shown in Fig. 2, which adopts a dual-loop control structure with an inner current loop and an outer position loop. The inputs of the sliding mode controller in the position loop include the load-side position reference command θ_{L-ref} , the feedback values of the actual position θ_L and speed ω_L , as well as the estimated torque information matrix $\hat{T}$ (which contains the information of T_{M-lump} and T_{L-lump}). The output of the controller is the q-axis current reference i_{q-ref} under the $i_{d-ref} = 0$ control strategy.

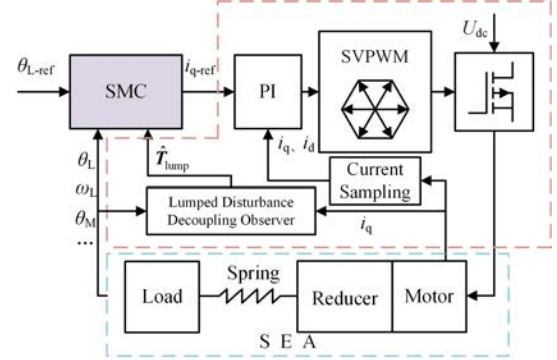


Fig. 2. Block diagram of sliding mode position control for FSS.

The design of the sliding mode controller mainly consists of two parts: sliding mode surface design and reaching law design. In TSMC strategies, constant-coefficient sliding mode surfaces are commonly adopted, such as linear sliding mode surfaces and terminal sliding mode surfaces. Common reaching laws include the constant velocity reaching law, the power reaching law, and the super-twisting reaching law. In comparison, the super-twisting reaching law has the advantages of low chattering and strong robustness, and is widely used in the research and engineering implementation of SMC [31]-[33]. In the following, the classic combination of the linear time-invariant sliding mode surface and the super-twisting reaching law is taken as an example for performance analysis.

By regarding the current loop of the motor as an ideal actuator, the FSS can be equivalent to a fourth-order two-inertia system. Therefore, four state variables are required for the design of the sliding mode controller, which are expressed as (4):

$$\begin{cases} x_1 = \theta_{L-ref} - \theta_L \\ x_2 = \dot{x}_1 = \dot{\theta}_{L-ref} - \omega_L \\ x_3 = \dot{x}_2 = \ddot{\theta}_{L-ref} - \frac{K_s}{J_L} \left(\frac{\theta_M}{N} - \theta_L \right) + \frac{T_{L-lump}}{J_L} \\ x_4 = \dot{x}_3 = \ddot{\theta}_{L-ref} - \frac{K_s}{J_L} \left(\frac{\omega_M}{N} - \omega_L \right) + \frac{\dot{T}_{L-lump}}{J_L} \end{cases} \quad (4)$$

where x_1 , x_2 , x_3 , and x_4 denote the position difference, speed difference, acceleration difference, and jerk difference, respectively.

The linear constant-coefficient sliding mode surface is selected as (5):

$$s_t = c_1 x_1 + c_2 x_2 + c_3 x_3 + c_4 x_4 \quad (5)$$

Differentiating the constant-coefficient sliding mode surface in (5) yields:

$$\dot{s}_t = c_1 \dot{x}_1 + c_2 \dot{x}_2 + c_3 \dot{x}_3 + c_4 \dot{x}_4 \quad (6)$$

The expression of $\dot{x}_4$ can be obtained by differentiating (4) and substituting (1) and (3) into the resulting derivative:

$$\begin{aligned} \dot{x}_4 = \ddot{\theta}_{L-ref} - \frac{K_t K_s i_{q-ref}}{N J_M J_L} + \frac{K_s^2}{J_L^2 N} (\theta_M - N \theta_L) + \\ \frac{K_s T_{M-lump}}{N J_M J_L} - \frac{K_s T_{L-lump}}{J_L^2} + \frac{\ddot{T}_{L-lump}}{J_L} \end{aligned} \quad (7)$$

To drive the system state points to reach the constant-coefficient sliding mode surface and perform sliding mode motion, a reaching law needs to be designed, and the super-twisting reaching law is designed as (8) [28]:

$$\dot{s}_t = -y_1 |s|^{\frac{1}{2}} \text{sgn}(s) + \int -y_2 \text{sgn}(s) \quad (8)$$

where $y_1, y_2 > 0$ are the coefficients of the reaching law.

Substituting (8) into (6), the control law of the q-axis reference current i_{q-ref} can be obtained as (9):

$$i_{q-ref} = \frac{N J_M J_L}{K_t K_s} (f_d + f_{st} + f_{st}) \quad (9)$$

where f_d denotes the component in the control law that is only related to the system dynamic model, which is given by (10):

$$f_d = \ddot{\theta}_{L-ref} + \frac{K_s^2}{J_L^2 N} (\theta_M - N \theta_L) + \frac{K_s T_{M-lump}}{N J_M J_L} - \frac{K_s T_{L-lump}}{J_L^2} + \frac{\ddot{T}_{L-lump}}{J_L} \quad (10)$$

where $\dot{}$ denotes the first derivative, $\ddot{}$ denotes the second derivative, and $\dddot{}$ denote the third derivative. f_{st} represents the component in the control law that is only related to the design of the sliding mode surface s , which is given by:

$$f_{st} = \frac{c_1}{c_4} x_2 + \frac{c_2}{c_4} x_3 + \frac{c_3}{c_4} x_4 \quad (11)$$

where f_{st} is the component in the control law related to the design of the reaching law, which is given by:

$$f_{st} = \frac{y_1 |s|^{\frac{1}{2}} \text{sgn}(s) + \int y_2 \text{sgn}(s)}{c_4} \quad (12)$$

Under common working conditions of point-to-point positioning such as position step commands and position ramp commands, the load-side position will inevitably go through a deceleration phase when approaching the target position. Due to the limited position bandwidth of the controller, the load-side position may fail to track the position command under certain working conditions. At this time, when the position command reaches the target position at $t = 2$ s, the acceleration reference value sent to the controller is 0 rad/s^2 , as shown in Fig. 3(a). However, the actual load-side acceleration is negative during the load-side deceleration phase, as depicted in Fig. 3(b). According to (4), the load-side acceleration error x_3 and jerk error x_4 are positive at this moment, as illustrated in Fig. 3(c). It can be seen from (11) that these two components provide a positive current

reference value in the deceleration phase. The corresponding electromagnetic torque is in the same direction as the current rotational speed, acting as an accelerating current and hindering the deceleration of the load side.

In addition to the overshoot caused by the linear constant-coefficient sliding mode surface, the integral term of the super-twisting reaching law will also induce overshoot in the position response. Taking the positive step of the given reference position as an example, it can be seen from (5) that the initial value of s is greater than 0, that is, the state point moves from the region of $s > 0$ to the sliding mode surface of $s = 0$. Combined with (12), the integral term of the super-twisting algorithm accumulates positive accelerating current during this movement process. Such accelerating current can only be gradually offset when the state point moves into the region of $s < 0$. In the region of $s < 0$, $x_1 < 0$ (the position error is less than 0), which means that overshoot occurs in the position response.

In summary, in the position control of the FSS, the traditional sliding mode position control strategy usually adopts a constant-coefficient sliding mode surface and a super-twisting reaching law. However, due to the existence of the elastic torsion spring, the dynamic order of the system is increased. To design a first-order sliding mode position controller, high-order differential terms, namely the

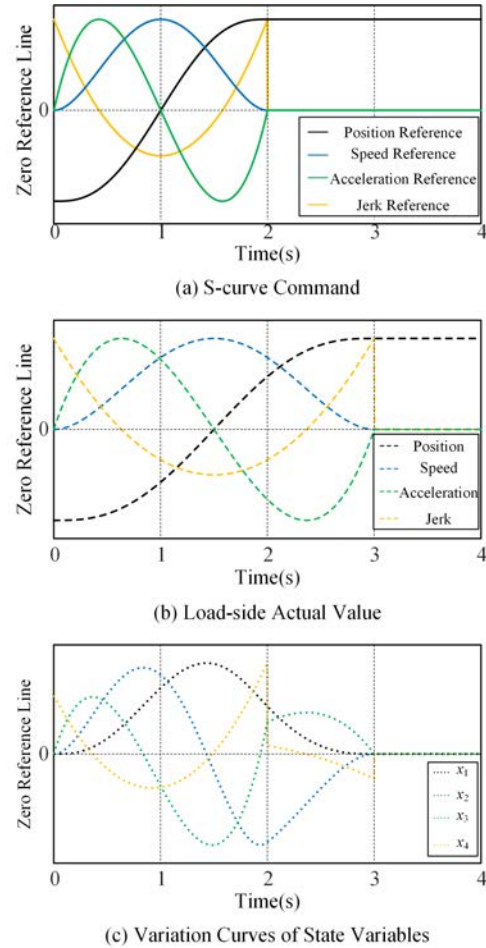


Fig. 3. Schematic diagram of positioning process with S-curve position command.

acceleration error term x_3 and the jerk error term x_4 , need to be added to the constant-coefficient sliding mode surface. The accelerating current provided by these terms during the deceleration phase will cause overshoot in the position response. In addition, the integral term in the super-twisting reaching law further aggravates this overshoot.

IV. GDG-SMC Strategy

To address the limitation that the TSMC strategy causes overshoot in the position response for FSS position control, this paper proposes a GDG-SMC strategy. Firstly, a GDG sliding mode surface is designed to reduce the accelerating current provided by the sliding mode surface component in the control law during the deceleration phase. Secondly, an anti-integral saturation super-twisting reaching law is developed to mitigate the influence of the super-twisting integral term in the control law on the deceleration phase, thereby reducing and even eliminating the overshoot of the position response. Finally, a lumped disturbance decoupling observer is constructed to acquire the motor-side lumped disturbance and load-side lumped disturbance required by the controller.

A. Design of GDG Sliding Mode Position Controller

To address the overshoot of the position response caused by the acceleration error term and the jerk error term in the aforementioned constant-coefficient sliding mode surface, a GDG sliding mode surface is designed in this paper, which is expressed as (13):

$$\begin{cases} s = c_1 h(x_1) x_1 + c_2 g(x_1) x_2 + c_3 x_3 + c_4 x_4 \\ h(x_1) = h_1 - h_2 e^{-\frac{x_1^2}{2m^2}}, g(x_1) = g_1 + g_2 e^{-\frac{x_1^2}{2n^2}} \end{cases} \quad (13)$$

where $h(x_1)$ and $g(x_1)$ are the GDG functions introduced into the sliding mode surface; h_1 and g_1 are the biases of the GDG functions, h_2 and g_2 are the peak values of the Gaussian functions, with $h_1, h_2, g_1, g_2 > 0$ and $h_1 > h_2$; $m, n > 0$ are the width parameters of the Gaussian functions, which are used to adjust the variation rate and action range of the dynamic gain with x_1 , so as to suppress the overshoot. The sliding mode surface coefficients c_1, c_2, c_3 , and c_4 are all set to positive values.

To address the position response overshoot caused by the integral term in the super-twisting reaching law, an anti-integral saturation super-twisting reaching law is designed in this paper, and its structural block diagram is shown in Fig. 4.

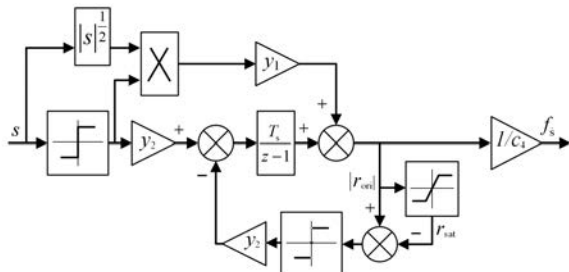


Fig. 4. Block diagram of the anti-integral saturation super-twisting reaching law.

This reaching law detects the absolute value of the sum of the proportional term and the integral term in real time to judge whether it exceeds the preset saturation value. When it is less than or equal to the saturation value, the negative feedback channel is closed, and the integral can be accumulated normally in the current control cycle; when it exceeds the saturation value, the negative feedback channel is opened to prevent the integral accumulation in the current control cycle, and the integral result of the previous control cycle is applied to the current control cycle, thus avoiding the saturation of the integral term. The mathematical expression of the designed anti-integral saturation super-twisting reaching law is shown in (14):

$$\dot{s} = -y_1 |s|^{\frac{1}{2}} \operatorname{sgn}(s) + \int -y_2 [\operatorname{sgn}(s) - \operatorname{sgn}(r_{\text{ori}} - r_{\text{sat}})] \quad (14)$$

where $y_1 > 0$ and $y_2 > 0$ are the coefficients of the reaching law; the original term of the anti-integral saturation super-twisting reaching law is defined as (15):

$$r_{\text{ori}} = y_1 |s|^{\frac{1}{2}} \operatorname{sgn}(s) + \int y_2 \operatorname{sgn}(s) \quad (15)$$

To avoid the saturation of the integral term, the integral is allowed to accumulate when $|r_{\text{ori}}| \leq r_{\text{sat}}$; the integral term is frozen when $|r_{\text{ori}}| > r_{\text{sat}}$, and no integral accumulation is performed in the current control cycle. r_{sat} denotes the saturation value of the original term of the anti-integral saturation super-twisting reaching law, which is given by $r_{\text{sat}} = I_{\text{sat}} \times c_4 \times K_t K_s / (N J_M J_L) \times \operatorname{sgn}(r_{\text{ori}})$, where I_{sat} is the q-axis saturation current.

Differentiating (13) yields:

$$\begin{aligned} \dot{s} = & c_1 \left(h_1 - h_2 e^{-\frac{x_1^2}{2m^2}} \right) x_2 + \frac{c_1 h_2 e^{-\frac{x_1^2}{2m^2}}}{m^2} x_1^2 x_2 + c_2 \left(g_1 + g_2 e^{-\frac{x_1^2}{2n^2}} \right) x_3 \\ & - \frac{c_2 g_2 e^{-\frac{x_1^2}{2n^2}}}{n^2} x_1 x_2^2 + c_3 x_4 + c_4 \dot{x}_4 \end{aligned} \quad (16)$$

Substituting (14) into (16), the q-axis reference current control law of the proposed controller can be obtained, that is:

$$i_{q\text{-ref}} = \frac{N J_M J_L}{K_t K_s} [f_d + f_s + f_{\text{st}}] \quad (17)$$

where f_d is given by (10). f_s represents the component in the control law that is only related to the design of the sliding mode surface s , which is given by:

$$\begin{aligned} f_s = & \frac{c_1 \left(h_1 - h_2 e^{-\frac{x_1^2}{2m^2}} \right)}{c_4} x_2 + \frac{c_1 h_2 e^{-\frac{x_1^2}{2m^2}}}{c_4 m^2} x_1^2 x_2 + \frac{c_2 \left(g_1 + g_2 e^{-\frac{x_1^2}{2n^2}} \right)}{c_4} x_3 \\ & - \frac{c_2 g_2 e^{-\frac{x_1^2}{2n^2}}}{c_4 n^2} x_1 x_2^2 + \frac{c_3}{c_4} x_4 \end{aligned} \quad (18)$$

where f_{st} is the component in the control law related to the design of the reaching law, which is given by:

$$f_{\text{st}} = \frac{y_1}{c_4} |s|^{\frac{1}{2}} \operatorname{sgn}(s) + \int \frac{y_2}{c_4} [\operatorname{sgn}(s) - \operatorname{sgn}(r_{\text{ori}} - r_{\text{sat}})] \quad (19)$$

The overall block diagram of the GDG sliding mode position controller is shown in Fig. 5.

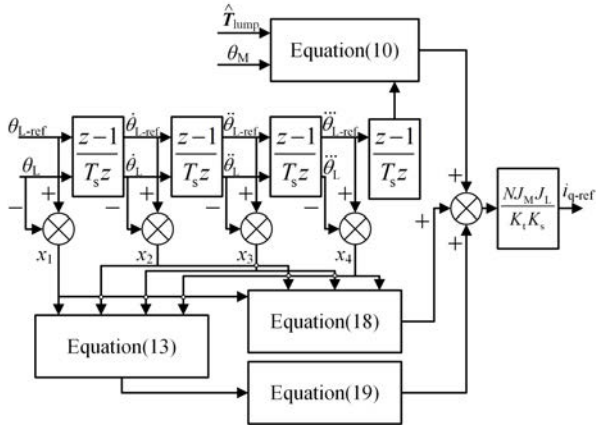


Fig. 5. Block diagram of the GDG sliding mode position controller.

B. Performance Analysis of the GDG-SMC Strategy

This section analyzes the advantages of the GDG-SMC strategy over the TSMC strategy.

Compared with the TSMC strategy, the proposed control strategy suppresses the accelerating current during the deceleration phase from the following three aspects, thereby reducing the overshoot of the position response.

1) The proposed control strategy adds two components conducive to load-side deceleration to the i_{q-ref} control law, as the second and fourth terms in (18). These two terms always provide decelerating current during the point-to-point positioning control process. The torque corresponding to this current is opposite to the rotational speed, which can effectively weaken the accelerating current components introduced by the feedback term of the acceleration error x_3 and the feedback term of the jerk error x_4 in the traditional control law during the deceleration phase.

2) The GDG in the proposed sliding mode surface enables the state point to reach the sliding mode surface $s = 0$ and even the region of $s < 0$ faster. During point-to-point positioning, when the load side approaches the target position, x_1 in (13) has the same sign as the initial value of s , and the coefficient $h(x_1)$ of this term decreases continuously; x_2 has the opposite sign to the initial value of s , and the coefficient $g(x_1)$ of this term increases continuously. Therefore, in point-to-point positioning, the proportion of the term x_1 with the same sign as the initial value of s is reduced, while the proportion of the term x_2 with the opposite sign to the initial value of s is increased. The proposed GDG sliding mode surface allows the state point to enter the region with the opposite sign to the initial value of s more quickly (for example, when the initial value of $s > 0$, the proposed sliding mode surface enables the state point to reach the region of $s < 0$ faster). Combined with (19), the s of the state point provides decelerating current through the reaching law component in the control law during the load-side deceleration phase, which further enhances the deceleration torque provided in the deceleration phase and thus suppresses the overshoot of the position response.

3) The proposed anti-integral saturation super-twisting reaching law reduces the possibility of overshoot in the

position response caused by integral term saturation. It can be seen from (19) that when $r_{ori} \geq r_{sat}$, the integral term no longer accumulates, and only the first power term plays a role at this time; the integral term starts to accumulate only when $r_{ori} < r_{sat}$, which effectively avoids the possibility of integral term saturation and further suppresses the overshoot of the position response.

Taking the positive position step command as an example: Under the two strategies of the proposed GDG-SMC and the TSMC in this paper, the dynamic response curves after the reference position steps from 0 to 2π rad are shown in Fig. 6. Under the proposed control strategy, x_1 is positive and x_2 is negative when the load side approaches the target position. Therefore, the second and fourth terms in (18) are negative, and the current component f_s provided by the sliding mode surface of the proposed strategy is smaller than that of the traditional control strategy, as shown in Fig. 6(c).

In addition, it can be seen from Fig. 6(f) that the state point is initially in the region of $s > 0$, which has the same sign as x_1 . As the load side approaches the target position, the coefficient of x_1 decreases, and the coefficient of x_2 increases in (13). Compared with the constant-parameter sliding mode surface (5), the proposed sliding mode surface (14) enables the state point to move to the region of $s = 0$ and even $s < 0$ faster. Thus, the current component f_s provided by the reaching law of the proposed strategy is smaller than that of the traditional control strategy, as shown in Fig. 6(d).

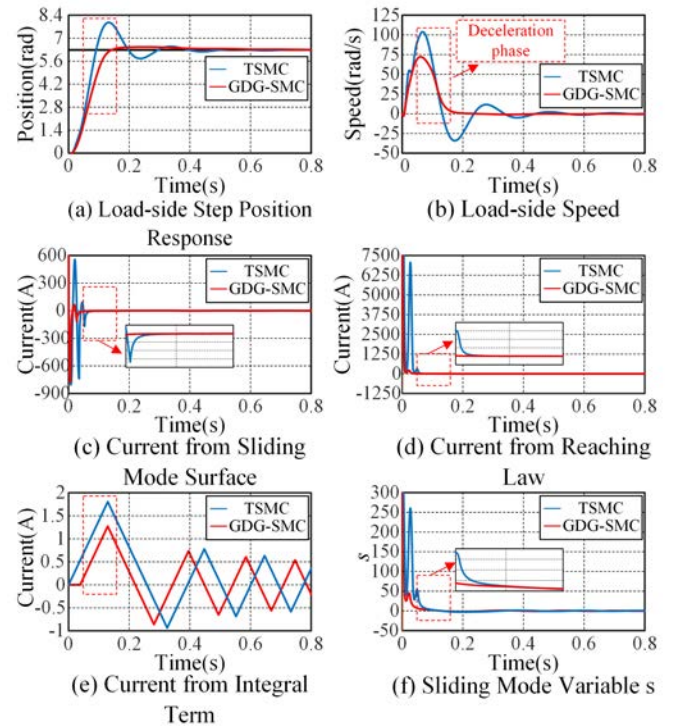


Fig. 6. Simulation waveforms of position step response under two control strategies.

Finally, as shown in Fig. 6(e), the positive current provided by the integral term in the proposed anti-integral saturation super-twisting reaching law is smaller during the deceleration phase, which is more conducive to the deceleration of the load side.

In summary, the proposed control strategy can achieve better deceleration on the load side, as shown in Fig. 6(b), thereby reducing the overshoot of the position response, as depicted in Fig. 6(a). Therefore, compared with the TSMC, the proposed GDG-SMC can effectively reduce the overshoot of the load-side position response under the point-to-point positioning condition.

C. Design of Lumped Disturbance Decoupling Observer

To clarify the relationship between Fig. 2 and this subsection, the torque observer in Fig. 2 is the proposed lumped disturbance decoupling observer. It estimates the motor-side and load-side lumped disturbance torques from the measured speeds, q-axis current, and elastic torsion deformation; the estimated values are then used in the sliding mode controller for disturbance compensation.

The decoupling observer constructed based on the sliding mode concept for the single-inertia system in [30] is extended to the FSS dual-inertia system in this paper, and a lumped disturbance decoupling observer is constructed to observe the lumped disturbances.

The lumped disturbance decoupling observer of the system is constructed according to (1) and (3), and its expression is shown in (20):

$$\begin{cases} s_{\text{lump}} = e = \hat{\omega} - \omega \\ \hat{\dot{\omega}} = J^{-1}(Ku - \hat{T}_{\text{lump}}) + kp \\ \hat{\dot{T}}_{\text{lump}} = gp - gk^{-1}\dot{e} \end{cases} \quad (20)$$

where $s_{\text{lump}} = [s_M, s_L]^T$ is the sliding mode surface vector of the lumped disturbance observer; $e = [e_M, e_L]^T$ is the error vector between the observed and measured rotational speed; $\hat{\omega} = [\hat{\omega}_M, \hat{\omega}_L]^T$ is the observed rotational speed vector; $\omega = [\omega_M, \omega_L]^T$ is the measured rotational speed vector; $J = \begin{bmatrix} J_M & 0 \\ 0 & J_L \end{bmatrix}$ is the moment of inertia matrix; $K = \begin{bmatrix} K_t & 0 \\ 0 & K_s \end{bmatrix}$ is the input gain matrix; $u = [i_q, \theta_M/N - \theta_L]^T$

is the input vector; $\hat{T}_{\text{lump}} = [\hat{T}_{M-\text{lump}}, \hat{T}_{L-\text{lump}}]^T$ is the observed lumped disturbance vector;

$k = \begin{bmatrix} k_M & 0 \\ 0 & k_L \end{bmatrix}$ is the switching gain matrix of the lumped

disturbance; $g = \begin{bmatrix} g_M & 0 \\ 0 & g_L \end{bmatrix}$ is the switching feedback gain

matrix of the lumped disturbance; $p = [\text{sgn}(e_M), \text{sgn}(e_L)]^T$ is the switching vector.

The structural block diagram of the lumped disturbance decoupling observer is shown as follows:

In summary, the GDG-SMC strategy proposed in this paper achieves two improvements:

1) a GDG sliding mode surface is proposed;

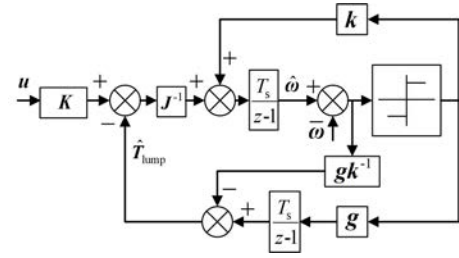


Fig. 7. Structure of the lumped disturbance decoupling observer.

2) The traditional super-twisting reaching law is improved. These two innovations suppress the overshoot of the position response from three aspects: (1) First, the improved sliding mode surface increases the decelerating current provided by the reaching law component in the deceleration phase; (2) Second, the improved sliding mode surface introduces two additional speed error term components into the sliding mode surface component of the q-axis reference current control law, which increases the decelerating current in the deceleration phase; (3) Finally, the anti-integral saturation super-twisting reaching law suppresses the overshoot caused by the integral component. Furthermore, the proposed sliding mode surface can maintain high dynamic response characteristics while suppressing the overshoot of the position response.

Remark 2 (main novelty): Different from existing SMC methods that mainly improve steady-state accuracy, chattering suppression, or finite-time convergence, this paper focuses on overshoot suppression in the transient deceleration phase of FSS. The proposed GDG-SMC is not a direct combination of Gaussian gain and super-twisting SMC. Instead, the GDG is designed according to the position error to redistribute the weights of the position and speed errors in the sliding surface, thereby increasing the braking-current component during deceleration. Meanwhile, the anti-integral-saturation super-twisting reaching law limits integral accumulation to avoid the overshoot induced by the reaching-law integral term. Therefore, the novelty lies in the deceleration-oriented sliding-surface reconstruction and reaching-law saturation design for overshoot-free point-to-point positioning of FSS.

V. STABILITY ANALYSIS OF THE GDG-SMC STRATEGY

The stability analysis of the GDG-SMC strategy includes the stability analysis of the proposed GDG sliding mode position controller and that of the lumped disturbance decoupling observer. The stability proof of the lumped disturbance decoupling observer is available in [30] and will not be elaborated further in this paper.

In addition, the observer estimation error enters the q-axis current command through the disturbance-compensation term in (10), and can be regarded as a bounded matched perturbation when the observer is stable. Therefore, the reachability of the sliding surface and the practical stability of the GDG-SMC controller are preserved under bounded observer errors. As the observer error converges, its influence on the control law also vanishes.

The stability of the sliding mode controller must satisfy the following two conditions:

- 1) The sliding mode surface is reachable, and the sliding mode is maintained;
- 2) The sliding mode motion makes the state points converge to the origin.

Condition 1 depends on the design of the reaching law, and Condition 2 depends on the design of the sliding mode surface.

The analysis of whether the proposed anti-integral saturation super-twisting reaching law satisfies Condition 1 includes the analysis of two cases: unsaturated and saturated states of the proposed reaching law.

Firstly, in the saturated state, A denotes the frozen integral value from the previous control cycle. In the digital implementation, this value is held by a zero-order hold within the current sampling period and can therefore be treated as a constant in the local Lyapunov analysis. Moreover, A is bounded by the anti-windup saturation mechanism. With:

$$V = \frac{1}{2} s^2 \quad (21)$$

one has:

$$\dot{V} = s\dot{s} \leq -y_1 |s|^{\frac{3}{2}} \text{sgn}(s) + |A||s| \quad (22)$$

Thus, the state is driven toward the bounded neighborhood $|s| \leq (|A|/y_1)^2$ during saturation. Once the reaching law returns to the unsaturated state, the standard super-twisting convergence analysis applies. Increasing y_1 or reducing r_{sat} decreases this boundary.

Secondly, the stability analysis of the unsaturated reaching law is consistent with that of the traditional super-twisting reaching law, which has been proved in [34]. In summary, the anti-integral saturation super-twisting reaching law ensures the stability of the system and enables the state point to converge to the sliding mode surface $s = 0$.

The following analysis is conducted to verify whether the GDG sliding mode surface satisfies Condition 2. Since the proposed sliding mode surface is a dynamic-gain sliding mode surface, different from the traditional constant-coefficient sliding mode surface, it is impossible to analyze whether the state points on the sliding mode surface can converge to the origin by deriving the expression of the convergence time. Therefore, the Lyapunov stability theorem is adopted in this paper to analyze whether the state points on the proposed GDG sliding mode surface can converge to the origin.

When $s = 0$, the sliding mode surface shown in (13) is expressed as (23):

$$0 = c_1 h(x_1) x_1 + c_2 g(x_1) x_2 + c_3 x_3 + c_4 x_4 \quad (23)$$

Therefore, the objective to be proved in this paper is the global asymptotic stability of the third-order nonlinear differential equation. According to [35], if there exist constants $\alpha > 0$ and $\beta > 0$ such that $\frac{c_3}{c_4} \geq \alpha$, $\beta \leq \frac{c_2}{c_4} g(x_1)$,

$0 < \left[\frac{c_1}{c_4} h(x_1) x_1 \right]' < \alpha\beta$, the zero solution of (23) satisfies the global asymptotic stability.

According to (13), let:

$$H(x_1) = \left[\frac{c_1}{c_4} h(x_1) x_1 \right]' = \frac{c_1}{c_4} h_1 + \frac{c_1}{c_4} h_2 \left(\frac{x_1^2}{m^2} - 1 \right) e^{-\frac{x_1^2}{2m^2}} \quad (24)$$

It can be obtained that $H(x_1)$ reaches its minimum value when $x_1 = 0$, and reaches its maximum value when $x_1 = \sqrt{3}m$, that is:

$$\frac{c_1}{c_4} (h_1 - h_2) \leq H(x_1) \leq \frac{c_1}{c_4} \left(h_1 + 2e^{-\frac{3}{2}} h_2 \right) \quad (25)$$

Therefore, ensuring:

$$\begin{cases} h_1 - h_2 > 0 \\ h_1 + 2e^{-\frac{3}{2}} h_2 < \alpha\beta \end{cases} \quad (26)$$

can guarantee that the zero solution of (23) satisfies global asymptotic stability. In summary, the GDG sliding mode position controller proposed in this paper is stable. Therefore, the GDG-SMC strategy proposed in this paper is stable.

The remaining observer estimation error enters the q-axis current law as a compensation error. When the observer error is bounded or convergent, it can be regarded as a bounded matched perturbation, and the robustness of the sliding mode controller guarantees practical closed-loop stability.

VI. EXPERIMENTAL VERIFICATION

To verify the effectiveness of the proposed control strategy, a scheme combining a PMSM and an elastic coupling is adopted to build the FSS experimental platform, as shown in Fig. 8.

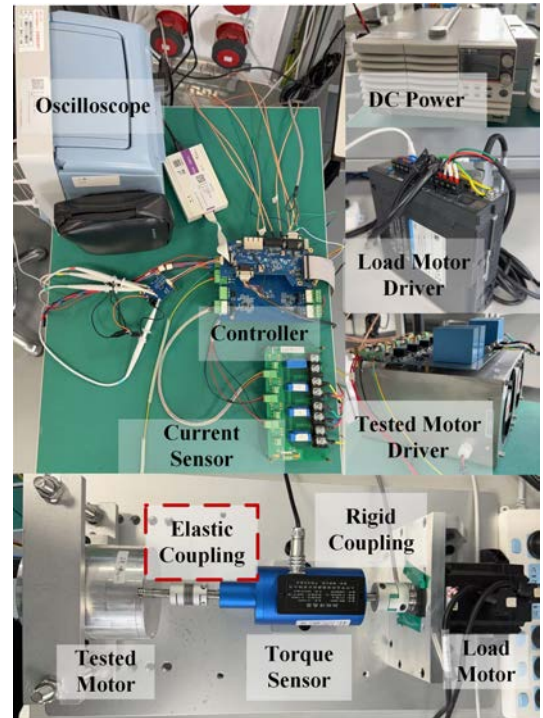


Fig. 8. Experimental test platform.

The tested motor is a 500W PMSM, equipped with a 2000-line encoder as the motor-side position sensor. Between the elastic coupling and the load motor, a 5000-line encoder is

installed as the load-side position sensor. A PMSM (MS1H1-75B30CB-A331R, Inovance, China) is adopted as the load motor, and the specific parameters of the above two motors are shown in Table I. The elastic torsional spring stiffness of the elastic coupling is 281 (N·m)/rad, which is identical to that of the LSEA3 flexible robot actuator unit from Landau.

TABLE I
PARAMETERS OF THE MOTORS USED IN THE EXPERIMENTAL PLATFORM

Parameter	Tested motor	Load motor
Pole pairs	10	None
Rated current/A	10.6	4.4
Rated torque/(N·m)	1.06	2.39
U_{dc}/V	48	24

The control strategy selected for comparison in this paper is the TSMC strategy described above. The control parameters of the traditional sliding mode position control strategy are set as follows: $c_1 = 20$, $c_2 = 0.01$, $c_3 = 1 \times 10^{-5}$, $c_4 = 1 \times 10^{-6}$, $y_1 = 5$, $y_2 = 1$, $g_M = 1$, $g_L = 0.5$, $k_M = k_L = -30$. For the proposed control strategy, the control parameters are set as $h_1 = 1.2$, $h_2 = 1$, $g_1 = 0.5$, $g_2 = 2$, $m = n = 0.1\theta_{L-ref}$, and the remaining control parameters are consistent with those of the traditional control strategy. A control frequency of 10 kHz is adopted for both strategies. The following four working conditions are used to simulate the conditions faced by each joint motor of the flexible manipulator during object grasping.

- 1) Point-to-point positioning with no load and an angular displacement of 2π under the position step command;
- 2) Point-to-point positioning with full load (rated load) and an angular displacement of 2π under the position step command;
- 3) Point-to-point positioning with no load and a travel of 2π under the position S-curve command;
- 4) Point-to-point positioning with full load and a travel of 2π under the position S-curve command;

Fig. 9 shows the experimental waveforms under Working Condition 1. The overshoot of the load-side position response under the TSMC strategy is 40.761%, while that under the GDG-SMC strategy is 1.53%, which is less than 2% (in this paper, the settling time is defined as the minimum time required for the response curve to rise from zero, reach and stay within the $\pm 2\%$ error band of the steady-state value), resulting in no effective overshoot. The settling time is 0.28768 s, with only a slight increase. The increase in settling time is related to the plateau effect, as shown in Fig. 9(b). Under the step command, the initial value of the FSS state point is far from the origin and the GDG sliding mode surface, and does not enter the state space region where integral action is allowed by the proposed anti-integral saturation super-twisting reaching law, so the integral term stops accumulating. When the FSS state point approaches the sliding mode surface, the current corresponding to the accumulated value in the previous motion is too small to drive the state point to the sliding mode surface immediately. Therefore, the slow accumulation of the integral term leads to the emergence of the plateau effect, and the current corresponding to this

process is shown in the red box in Fig. 9 (f). The larger the integral gain, the shorter the duration of the plateau effect.

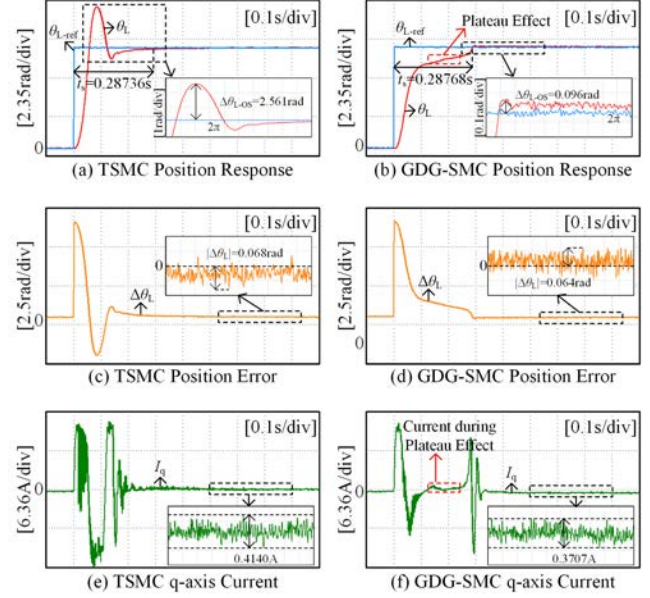


Fig. 9. Experimental waveforms of no-load step response under two control strategies.

Compared with the TSMC strategy, the GDG-SMC strategy greatly reduces the overshoot of the load-side position response by 96.24%, while the settling time is only slightly increased by 0.11%. Therefore, the proposed method maintains the convergence rate unchanged while significantly suppressing the overshoot. It not only effectively suppresses the overshoot of the load-side position response, but also preserves the high dynamic response performance of the system.

In addition, under the GDG-SMC strategy, the maximum steady-state error of the load-side position of the FSS in steady state is reduced to 0.064 rad, which is 1.02% of the reference command, achieving high positioning accuracy and excellent steady-state performance. Furthermore, the proposed anti-integral saturation super-twisting reaching law offsets the excessive accumulation of the integral term by setting the allowable integral region, thereby reducing the current chattering. The current chattering is reduced from 0.4140 A under TSMC to 0.3537 A under the proposed strategy, a reduction of 14.57%, which effectively attenuates the current chattering.

Fig. 10 shows the experimental waveforms under Working Condition 2. Under the GDG-SMC strategy, the peak value of the load-side position response of the FSS is 6.350 rad, with an overshoot of 1.07%, which is less than 2%, resulting in no effective overshoot. The settling time is 0.24288 s, with only a slight increase. Compared with the TSMC strategy, the GDG-SMC strategy greatly reduces the overshoot of the load-side position response by 93.23%, while the settling time is only slightly increased by 0.13%.

In addition, under the GDG-SMC strategy, the maximum steady-state error of the load-side position of the FSS in steady state is 0.0283 rad, which is 1.32% of the reference

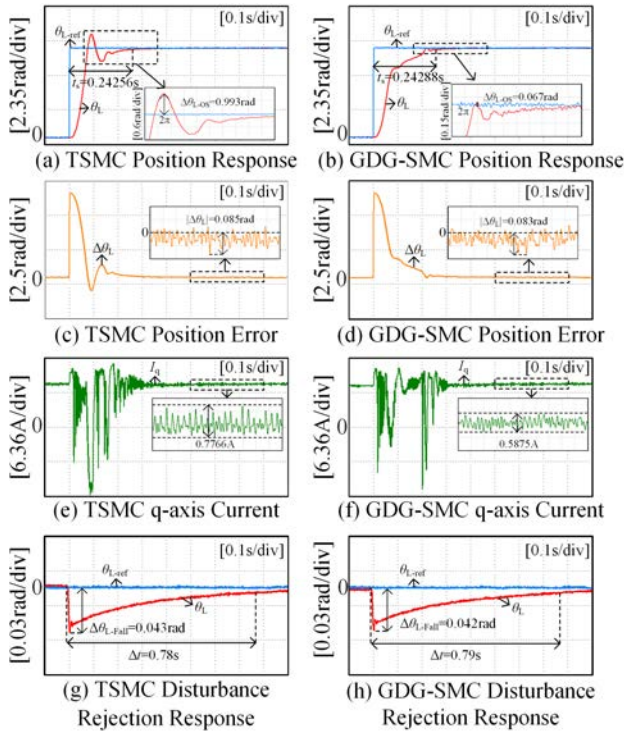


Fig. 10. Experimental waveforms of full-load step response under two control strategies

command, achieving high positioning accuracy and excellent steady-state performance. Furthermore, the current chattering is reduced from 0.7766 to 0.5875 A, a reduction of 24.35%, which effectively attenuates the current chattering.

Figs. 10(g) and 10(h) show the response curves of the two control strategies under the sudden application of rated load torque disturbance to the FSS. Under the GDG-SMC strategy, the maximum load-side position drop is 0.042 rad, and the recovery time to return to the $\pm 2\%$ error band of the steady-state value is 0.79 s, both of which are comparable to the indexes under the TSMC strategy. The proposed GDG-SMC strategy not only does not degrade the disturbance rejection capability of the system, but also significantly suppresses the overshoot of the load-side position response.

Fig. 11 shows the experimental waveforms under Working Condition 3 and Working Condition 4. When rapid positioning is required under the S-curve command, the overshoot of the proposed strategy is reduced from 9.43% to 2.09% under the no-load working condition, and from 11.22% to 3.28% under the full-load working condition. Furthermore, the settling time of the proposed strategy is significantly shorter than that of the traditional strategy.

In addition, the test results show that the program execution time of the traditional sliding mode position control strategy is 5.36 μ s, while that of the proposed control strategy is 7.16 μ s. The proposed strategy does not cause excessive extension of the execution time, with an increment of only 1.8 μ s, and the time consumption is still within a reasonable range.

In summary, the experimental results of the four working conditions in this paper are presented in the bar chart shown in Fig. 12. While maintaining excellent disturbance rejection

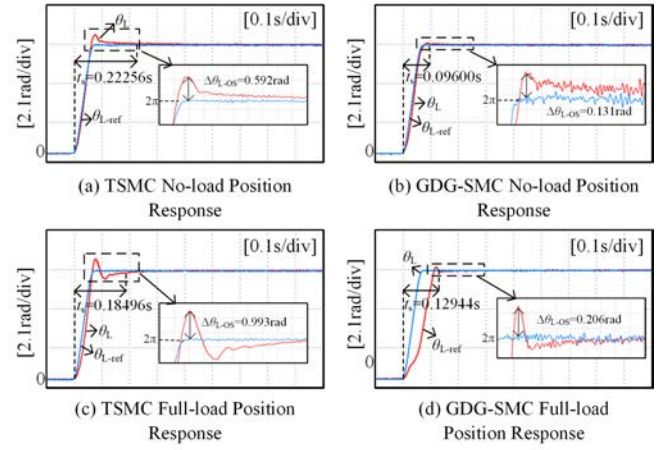


Fig. 11. Experimental waveforms of two control strategies under position S-curve command

performance and dynamic response capability, the GDG-SMC proposed in this paper can effectively suppress position overshoot for most point-to-point positioning commands.

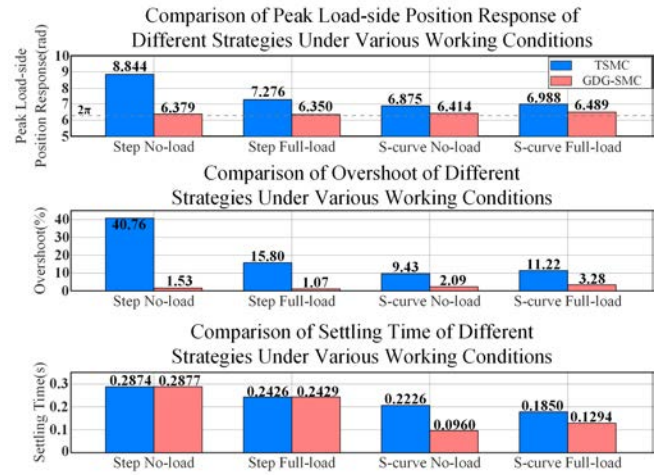


Fig. 12. Summary bar chart of experimental results

Limitations and practical considerations: The proposed method introduces additional parameters and requires motor-side/load-side position feedback and disturbance observation. Therefore, the tuning complexity is higher than that of basic TSMC. In addition, when the positioning amplitude changes significantly, the width parameters of the Gaussian functions should be adjusted according to the command amplitude. If severe measurement noise or unmodeled flexible modes appear near the control bandwidth, filtering and conservative gain selection are required. These issues will be further addressed by automatic parameter optimization in future work.

VII. CONCLUSION

This paper focuses on addressing the inherent problem of position response overshoot when the sliding mode position control strategy is applied to FSS. To solve this problem, this paper first conducts an in-depth analysis and points out that the constant-coefficient sliding mode surface in the traditional SMC strategy is the main cause of overshoot. To address this

limitation, the innovations and contributions of this paper are proposed as follows:

1) A Gaussian dynamic gain sliding mode surface is proposed. The control coefficients can be adjusted in real time according to the operating state during system operation, which enhances the deceleration current and effectively suppresses the overshoot of the load-side position response.

2) An anti-integral saturation super-twisting reaching law is proposed, which optimizes the integral term of the super-twisting reaching law to limit it within a reasonable range, thus effectively suppressing the position response overshoot caused by integral saturation.

3) The proposed GDG-SMC strategy achieves excellent performance in suppressing the positioning overshoot of flexible manipulators, and can provide a theoretical basis and technical support for the precise position control of such systems.

VIII. ACKNOWLEDGEMENT

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Zhichen Lin was born in Yantai, China, in 1993. He received his B.S. degree in electrical engineering from Dalian Maritime University, Dalian, China, in 2016, and the Ph.D. degree in electrical engineering from Tianjin University, Tianjin, China, in 2021.

He worked as a Postdoctoral Researcher at Zhejiang University from 2021 to 2024. He is currently an Associate Researcher with the Zhejiang University Advanced Electrical Equipment Innovation Center, Hangzhou, China. His research interests include electrical machines, motor drives, and power electronics.



Chendong Zhang was born in Xinxiang, China, in 2000. He received the B.S. degree in electrical engineering from Guangdong University of Technology, Guangzhou, China, in 2023.

He is currently working toward the M.S. degree in electrical engineering in the College of Electrical Engineering, Zhejiang University, Hangzhou, China. His research interests include electrical machines and servo motor drives.



Zhiqiang Wang (Member, IEEE) was born in Tianjin, China, in 1984. He received the B.S. degree from the Hebei University of Technology, Tianjin, China, in 2006, and the M.S. and Ph.D. degrees from Tianjin University, Tianjin, in 2008 and 2012, all in electrical engineering.

He is currently an Associate Professor with the School of Electrical Engineering, Tiangong University, Tianjin. His research interests include power electronics technology and intelligent control of motor systems.



Tingna Shi (Senior Member, IEEE) was born in Yuyao, China, in 1969. She received the B.S. and M.S. degrees from Zhejiang University, Hangzhou, China, in 1991 and 1996, respectively, and the Ph.D. degree from Tianjin University, Tianjin, China, in 2009, all in electrical engineering.

She is currently a Professor with the College of Electrical Engineering, Zhejiang University. Her current research interests include electrical machines and their control systems, power electronics, and electric drives.