Postprint: Super-Twisting Terminal Sliding Mode Antenna Servo Control Method Based on Disturbance Observer

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Abstract

Pointing accuracy constitutes a critical metric for evaluating radio telescope antenna performance, with servo control methodology serving as a key determinant of this metric. This study proposes a super-twisting terminal sliding mode control approach based on a disturbance observer, achieving global robust finite-time stability for antenna servo systems while analyzing convergence time through Lyapunov stability theory. The proposed method employs a state-dependent variable exponent coefficient for the sliding mode variable, which fixes the maximum sliding duration and thereby enhances system robustness. The disturbance observer accurately captures disturbances in the servo system, and when combined with the control law of a variable-gain super-twisting algorithm featuring a second-order structure, effectively mitigates chattering phenomena to realize robust antenna control. Simulation results demonstrate that the system can rapidly track signals within approximately 0.55;s, exhibiting small tracking errors and significant chattering suppression. The proposed control strategy enables more rapid, simpler, and more effective tracking of reference signals while suppressing disturbances in antenna servo systems. }

Full Text

Preamble

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Research on Antenna Servo Control Method Based on Super-Twisting Terminal Sliding Mode with Disturbance Observer

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Abstract

Pointing accuracy is a critical metric for evaluating radio telescope antenna performance, and the servo control method is a key factor affecting this indicator. This study proposes a super-twisting terminal sliding mode control method based on a disturbance observer to achieve global robust finite-time stability of the antenna servo system. The system's convergence time is analyzed using Lyapunov stability theory. The sliding mode variable in the proposed method employs a state-dependent variable exponential coefficient that fixes the maximum sliding time and enhances system robustness. The disturbance observer can accurately capture servo system disturbances, and when combined with the control law of a second-order variable-gain super-twisting algorithm, it effectively alleviates chattering phenomena and achieves robust antenna control. Simulation results demonstrate that the system can rapidly track signals in approximately 0.55 seconds with small tracking errors and significant chattering suppression. The proposed control strategy can track reference signals faster, more simply, and more effectively while suppressing interference in antenna servo systems.

Keywords techniques: radio telescopes, high angular resolution, nonlinear control, methods: data analysis

1 Introduction

As radio telescopes develop toward larger apertures, higher frequencies, and higher pointing accuracy, high-precision antenna control faces enormous challenges. The real-time state of large-aperture antennas is affected by various disturbances, making accurate mathematical modeling difficult and increasing control complexity. These disturbances primarily originate from antenna transmission mechanism wear and aging, structural thermal deformation causing equipment parameter perturbations, structural flexible vibrations, unmodeled dynamics, and environmental changes, all of which impact the precise pointing of large-aperture antennas. Astronomical observation is a dynamic process of exploring and tracking targets, making it a critical and urgent problem to ensure that antenna servo control systems possess stronger anti-interference characteristics and better dynamic performance.

Servo control methods play a crucial role in improving antenna pointing accuracy. The classical Proportional-Integral-Derivative (PID) controller is currently the most commonly used method for antenna servo control, but PID control struggles to meet the high-precision control requirements of modern antennas. While Linear Quadratic Gaussian (LQG) and H∞ controllers have improved pointing accuracy, they depend on precise antenna models. Quantitative Feedback Theory (QFT) can be applied to systems with high uncertainty but requires quantitative analysis and design. Linear Active Disturbance Rejection Control (LADRC) compensates for disturbances through a state observer, improving interference suppression capability but suffering from long convergence times that cannot be estimated.

Sliding Mode Control (SMC) is widely applied in industrial control, aerospace, and robotics due to its robustness and fast response characteristics. SMC can satisfy the requirements of large telescopes that are difficult to model precisely and need to overcome disturbances such as wind loads to achieve ideal closed-loop performance, attracting increasing attention from researchers in telescope servo control technology. Liang et al. applied disturbance observers and sliding mode control to tilt-axis telescopes. Liu et al. also applied sliding mode control to telescope servo systems, improving system robustness, but their design employed Linear Sliding Mode Control (LSMC) with a linear sliding surface, resulting in long system state convergence times. Terminal Sliding Mode Control (TSMC) utilizes nonlinear functions in sliding surface design, effectively improving convergence speed and enabling system states to converge to zero in finite time.

However, the upper bound of finite-time convergence stability depends on the system's initial state. Fixed-time convergence is an extension of finite-time convergence that is independent of the initial state and allows the convergence time upper bound to be predetermined based on parameters. Therefore, compared with the asymptotic stability of classical LSMC, TSMC offers advantages such as faster convergence, stronger robustness, and predictable convergence time, making it more suitable for astronomical observations with strict time response constraints. Nevertheless, common SMC methods typically employ discontinuous control inputs, inevitably causing system chattering. This chattering phenomenon affects precise positioning, increases motor wear, and results in large control inputs that are difficult to implement, making chattering suppression a research hotspot in sliding mode control.

To suppress chattering, researchers have proposed higher-order sliding mode methods, among which the Super-Twisting Algorithm (STA) is one of the best practical options. STA obtains continuous control by integrating the discontinuous control variable onto the derivative of the sliding variable, causing the system trajectory to converge to the origin in a spiral twisting manner within finite time. This approach solves the problem of discontinuous input while retaining the advantages of traditional sliding mode control. However, STA requires prior knowledge of disturbance bounds and does not allow time-varying disturbances. Gonzalez et al. designed a Variable Gain Super-Twisting Algorithm (VGSTA) that can handle time-varying and state-dependent disturbances, with gains adjusted according to state-dependent disturbance bounds. VGSTA precisely compensates for a priori unknown disturbances, achieving dynamic control inputs desired for engineering applications. Kuang et al. used VGSTA to improve wafer stage tracking performance in semiconductor manufacturing systems with friction. However, these new algorithms have seen limited application in antenna technology.

To address the requirements of high precision, anti-interference, fast response, and simple implementation for antenna servo control systems, this paper proposes a Super-Twisting Terminal Sliding Mode Control based on Disturbance Observer (STTSMCDO) method. The disturbance observer offers simple design, accurate observation, and improved system robustness. By using the disturbance observer to maximally compensate for disturbance variations, uncompensated disturbances are addressed through a variable exponential function dependent on system states in the sliding surface, enabling rapid convergence of system state variables and sliding variables to the sliding surface within finite time, with system states sliding to the equilibrium point in fixed time. Through simulation and comparison of different algorithms tracking angular position and angular velocity processes in antenna servo control systems, the superiority of the proposed algorithm is verified.

2 Antenna Servo System Controller Design

Antenna servo systems typically employ a 2-degree-of-freedom structure, adjusting azimuth and elevation angles simultaneously for observation. Azimuth and elevation control can be considered as two independent control loops and can be modeled separately. Taking azimuth control as an example, we establish the system's dynamic model by treating the load as a mass point supported by a massless rigid rod system. The antenna's moment of inertia is calculated using the parabolic dish's rotational inertia. The complete antenna system model includes a drive model (servo motor) and a transmission model (gearbox and load). The gearbox is a transmission box that can be viewed as two gears connected by a rod, with the primary side connected to the drive model and the secondary side connected to the load.

2.1 Dynamic Model of Antenna Servo System

The antenna servo system considers an AC servo motor with friction and a two-stage gearbox. The motor vector control employs $i_d = 0$ current control. The antenna's mechanical model is given by:

$$
\begin{aligned}
u_d &= Ri_d + L\frac{di_d}{dt} - p\omega_m L i_q; \\
u_q &= Ri_q + L\frac{di_q}{dt} + p\omega_m L i_d + p\omega_m \psi_f; \\
K_T i_q &= \left(\frac{2}{N_1}\right)^2 J\ddot{\theta}_m + \left(\frac{2}{N_1}\right)^2 B\dot{\theta}_m + N_2\left(\frac{2}{N_1}\right) K_L\theta_L; \\
\dot{\theta}_m &= \omega_m,
\end{aligned}
$$

where R is stator resistance, L is stator inductance, ψ_f is the permanent magnet flux linkage, p is the number of pole pairs, ω_m is the motor rotational angular velocity, i_d, i_q, u_d, u_q are the d-axis and q-axis currents and voltages respectively, K_T is the electromagnetic torque constant, K_{12} is the gear torque constant related to materials, $\ddot{\theta}_x, \dot{\theta}_x, \theta_x$ represent rotational angular acceleration, velocity, and displacement respectively, J_x represents moment of inertia, B_x represents viscous friction coefficient, and N_x is the gear transmission ratio. The subscript $x = m$ denotes the motor, $x = 1, 2$ denotes the primary and secondary sides of gears in the gearbox, and $x = L$ denotes the load.

Let $J_m + J_2 = J$, $B_m + B_2 = B$, $K_{12} = K$, and define the parameter variations: moment of inertia variation ΔJ, viscous friction coefficient variation ΔB, gearbox torque constant variation ΔK_{12}, motor torque constant variation ΔK_T due to environmental changes, and unknown disturbance D. The total system disturbance Δ is bounded and given by:

$$
\Delta = \Delta J\ddot{\theta}_m + \Delta B\dot{\theta}_m + \Delta K\theta_m + \Delta K_L\theta_L + \Delta K_T i_q + D.
$$

The mechanical motion equation of the antenna servo system can then be written as:

$$
J\ddot{\theta}_m + B\dot{\theta}_m + K\theta_m - K_L\theta_L = K_T i_q + \Delta.
$$

Select state variables $x_1 = \theta_m$, $x_2 = \dot{\theta}_m$, $x_3 = d = \Delta$ as the disturbance that cannot be measured. Here, $f = -\frac{B}{J}\dot{\theta}_m - \frac{K}{J}\theta_m + \frac{K_L}{J}\theta_L$ represents information obtained from position and velocity feedback, $g = \frac{K_T}{J}$ is a function related to the motor torque constant, and u is the controller input.

2.2 Disturbance Observer Design

The disturbance observer is designed as:

$$
\begin{aligned}
\dot{\hat{x}}_2 &= f + gu + \hat{x}_3 - k_1(\hat{x}_2 - x_2); \\
\dot{\hat{x}}_3 &= -k_2(\hat{x}_2 - x_2),
\end{aligned}
$$

where $k_1 > 0$, $k_2 > 0$, $\hat{x}_2$ is the estimate of $\dot{\theta}_m$, and $\hat{x}_3$ is the estimate of d.

Establish a Lyapunov function $V_D = \frac{1}{2}\tilde{x}_2^2 + \frac{1}{2}\tilde{x}_3^2$, where $\tilde{x}_i = \hat{x}_i - x_i$ is the error between actual and estimated values. Differentiating V_D yields:

$$\dot{V}_D = \tilde{x}_2(\tilde{x}_3 - k_1\tilde{x}_2) + \tilde{x}_3(\dot{x}_3 - k_2\tilde{x}_2) = -k_1\tilde{x}_2^2 \leq 0,$$

where $k_1 > 0$. From previous analysis, the total disturbance is bounded, and the disturbance is slowly varying, i.e., $\lim_{t\to\infty} \dot{d} = 0$. When $\dot{V}_D \equiv 0$, $\tilde{x}_2$ and $\tilde{x}_3$ will asymptotically converge to the desired equilibrium point. According to LaSalle's invariance principle, as $t \to \infty$, $\tilde{x}_3 \to 0$, meaning $\tilde{d} \to 0$, and the observer can rapidly estimate disturbances.

2.3 Controller Design

2.3.1 Controller Design Design a sliding surface with variable exponential coefficients:

$$s = \dot{e} + c_1[e]^{\frac{\sigma e^2}{1+\mu e^2}} + c_2 e,$$

where $[x]^k = |x|^k \text{sign}(x)$, $\text{sign}(x)$ is the sign function, $\frac{\sigma}{1+\mu} > 1$, and σ, μ, c_1, c_2 are all positive. x_d is the desired position signal, and $x_d, \dot{x}_d, \ddot{x}_d$ are continuous functions. The position tracking error is $e = x_1 - x_d$.

The motion model of the antenna servo system can be written in state equation form:

$$\begin{aligned} \dot{x}_1 &= x_2; \\ \dot{x}_2 &= f + gu + x_3; \\ \dot{x}_3 &= 0. \end{aligned}$$

The sliding mode control law is:

$$u = u_{eq} + u_{sc},$$

where u_{eq} is the equivalent control law and u_{sc} is the variable-gain super-twisting switching control law.

The switching control law u_{sc} is used to eliminate disturbances and drive the sliding variable s to converge to zero, causing tracking errors and system states to approach the sliding surface:

$$u_{sc} = -h_1(x)\phi_1(s) - \int h_2(x)\phi_2(s)\, dt,$$

where

$$\phi_1(s) = [s]^{\frac{1}{2}} + h_3 s;$$
$$\phi_2(s) = \phi_1'(s)\phi_1(s) = \text{sign}(s) + h_3[s]^{\frac{1}{2}}.$$

The control gains h_1, h_2, h_3 are non-negative and given by:

$$h_1(x) = \frac{-P_1P_2P_3}{\sqrt{P_3(P_1D_1 - P_3D_2)^2 + (-P_3D_1 - P_2D_2)^2 - P_1P_2P_3^2}} + h_2(x);$$
$$h_2(x) = h_1 - \frac{P_1}{\sqrt{P_3(P_1D_1 - P_3D_2)^2 + (-P_3D_1 - P_2D_2)^2 - P_1P_3^2}},$$

where $P = \begin{pmatrix} P_1 & P_3 \\ P_3 & P_2 \end{pmatrix}$ with $P_1 > 0$, $P_3 < 0$, and $P_1P_2 > P_3^2$.

The equivalent control law u_{eq} maintains system states on the sliding surface when disturbances are not considered (i.e., $s = 0$):

$$u_{eq} = \frac{[c_1A(e) + c_2](x_2 - \dot{x}_d) + f(x) - \ddot{x}_d}{g},$$

where $A(x) = \frac{\sigma}{2}\frac{\ln(|x|^{\mu}+1)+\mu x^2}{(1+\mu x^2)^2|x|^{\frac{\sigma x^2}{1+\mu x^2}+1}}$.

2.3.2 Stability Analysis With the super-twisting sliding mode control law, the derivative of the sliding variable becomes:

$$\dot{s} = -h_1(x)\phi_1(s) + z + d_1(s,t);$$
$$\dot{z} = -h_2(x)\phi_2(s) + \dot{d}_2(t),$$

where z is the second-order expression of the super-twisting control law, and the disturbance can be written as $d = d_1(s,t) + \dot{d}_2(t)$. The terms $|d_1(s,t)|$ and $|\dot{d}_2(t)|$ are bounded, with $|d_1(t)| \leq D_1|\phi_1(s)|$ and $|\dot{d}_2(t)| \leq D_2|\phi_2(s)|$ for $D_1, D_2 > 0$.

Let $Z^T = [\phi_1(s) \quad z]$. For the quadratic Lyapunov function $V(z) = Z^TPZ$, its derivative is:

$$\dot{V}(z) = -|s|^{-\frac{1}{2}}Z^TQZ,$$

where $Q = \begin{pmatrix} h_1 - \frac{d_1(s,t)}{\phi_1(s)} & -\frac{\dot{d}_2(t)}{\phi_2(s)} \\ -\frac{\dot{d}_2(t)}{\phi_2(s)} & h_2 \end{pmatrix}$ is a symmetric matrix.

Choosing $h_3 > 0$, $\phi'(s) > 0$, and making Q positive definite ensures $\dot{V}(z) < 0$. This guarantees that the sliding variable s converges to zero in finite time, while the position tracking error e and its derivative $\dot{e}$ converge to zero, ensuring global stability and that the state vector can track the desired trajectory.

2.3.3 Convergence Time Analysis The control input constrains the system's sliding dynamics on the sliding surface, driving the system trajectory toward the equilibrium point. The time for the state vector to approach the equilibrium from the initial state can be divided into two parts: the reaching phase and the sliding phase.

First Part: Sliding Motion Process

The sliding motion process occurs when the system state vector moves from the initial state x_0 toward the equilibrium point on the sliding surface (i.e., $s = 0$). The sliding time is $T(x)$. From equation (7):

$$\dot{e} = -c_1[e]^{\frac{\sigma e^2}{1+\mu e^2}} - c_2 e.$$

Choosing the Lyapunov function $V(e) = e^2$ and differentiating:

$$\dot{V}(e) = 2e\dot{e} = -2c_1|e|^{\frac{\sigma e^2}{1+\mu e^2}+1} - 2c_2 e^2.$$

When $V(e) \leq 1$, $\min(|e|^{\frac{\sigma e^2}{1+\mu e^2}}) > \min(|e|^{\frac{\sigma e^2}{2}}) = E^{-\sigma}$ where E is the natural constant with $\ln(E) = 1$. The sliding time $T_1(e)$ is:

$$T_1(e) \leq \frac{1}{2c_1 E^{-\sigma}} \ln\left(\frac{V^{1-\frac{\sigma}{2E}}(e_0)}{V(e)}\right).$$

When $V(e) > 1$, let $\frac{\sigma e^2}{2} > 1$, $e < e^{\eta+1}$, $\frac{\sigma e^2}{1+\mu e^2} = \gamma$, and $\frac{\sigma}{1+\mu} = \eta$, then:

$$T_2(e) \leq \int_{V(e_0)}^{V(e)} \frac{dV(e)}{-2c_1 V^{\frac{\eta+1}{2}}(e) - 2c_2 V(e)} = \frac{1}{c_2(\eta-1)} \ln\left(\frac{c_1 + c_2 V^{\eta-1}(e_0)}{c_1 + c_2 V^{\eta-1}(e)}\right).$$

Combining these two time periods, the system state vector reaches the origin from the initial state x_0 within fixed time $T(e)$, which satisfies:

$$T(e) = T_1(e) + T_2(e) \leq \frac{1}{c_2(\eta-1)} \ln\left(1 + \frac{c_2}{c_1}\right) + \frac{E^\sigma}{2c_1}.$$

Second Part: Reaching Motion Process

The reaching motion process occurs when the sliding variable approaches the sliding surface from the initial state s_0, with reaching time $T(s)$. Let $\|Z\|_2 = \sqrt{s^2 + z^2}$ be the 2-norm of Z. It can be shown that:

$$\lambda_{\min}\{P\}\|Z\|_2^2 \leq Z^T P Z \leq \lambda_{\max}\{P\}\|Z\|_2^2,$$

and

$$-\lambda_{\max}\{Q\}\|Z\|_2^2 \leq -Z^T Q Z \leq -\lambda_{\min}\{Q\}\|Z\|_2^2.$$

From equation (13):

$$\dot{V}(z) \leq -\frac{|s|^{-\frac{1}{2}} + h_3}{\lambda_{\max}\{P\}}\lambda_{\min}\{Q\}V(z) = -M_1 V^{\frac{1}{2}}(z) - M_2 V(z),$$

where $M_1 = \frac{\lambda_{\min}\{Q\}}{\lambda_{\max}\{P\}}$ and $M_2 = \frac{\lambda_{\min}\{Q\}}{\lambda_{\max}\{P\}}h_3$.

The sliding variable reaches the sliding surface from the initial state s_0 in finite time, with reaching time $T(s)$:

$$T(s) = \frac{2}{M_1}V^{\frac{1}{2}}(s_0, z_0) + \frac{1}{M_2}\ln\left(1 + \frac{M_2}{M_1}V^{\frac{1}{2}}(s_0, z_0)\right),$$

where $s_0, z_0 > 0$.

In summary, from equations (18) and (22), the closed-loop system reaches the equilibrium state from the initial state within finite time $T \leq T(e) + T(s)$.

3 Simulation and Experimental Verification

3.1 Fixed-Time Convergence Sliding Surface Verification

The designed variable exponential coefficient sliding surface (7) is verified for fixed-time convergence. With parameters $\sigma = 3$, $\mu = 1$, $c_1 = 2$, $c_2 = 2$, the convergence curves of position error and velocity error for different initial states $x_0 = 0.1, 0.5, 1, 3, 5, 10, 20$ are shown in Figure 1 [Figure 1: see original paper].

From equation (18), the maximum convergence time for state variables sliding on the sliding surface is calculated as $T(e) \leq 1.1401$ seconds, which matches the convergence time in Figure 1. The convergence curves show that regardless of how far the initial conditions are from the equilibrium point, all convergence curves essentially coincide after 0.75 seconds, with different states converging almost vertically to the sliding surface in the initial instant, independent of the initial state.

3.2 Sinusoidal Tracking Experiment for Antenna

The transfer function for a large-aperture telescope antenna system with permanent magnet synchronous motor is:

$$G(s) = \frac{1900s}{68.495s^2 + 4636s + 16537.86}.$$

The desired position signal is set as a sinusoid $x_d = \sin(t)$. A disturbance signal $d(t) = 2\sin(0.5t)$ is added after 5 seconds of system operation. The initial state of the controlled plant is $[x_{10} \quad x_{20}]^T = [0 \quad 0]^T$.

Four control algorithms are selected for comparison with parameters as follows:

- **STTSMCDO**: Uses sliding surface (12) and controller (13)-(16) with parameters $\sigma_1 = 2$, $\mu_1 = 0.1$, $c_1 = 2$, $c_2 = 9$, $h_3 = 2$, $a = 2$, $b = 1$.
- **Fixed-time Sliding Mode Controller (FXSMC)**: Sliding surface $s = \dot{e} + c_1[e]^{\frac{\sigma_1 e^2}{1+\mu_1 e^2}} + c_2[e]^{\frac{\sigma_2 e^2}{1+\mu_2 e^2}}$ with parameters $\sigma_1 = 3$, $\mu_1 = 1$, $\sigma_2 = 4$, $\mu_2 = 1$, $c_1 = 2$, $k_1 = 4$, $k_2 = 4$.
- **Linear Sliding Mode Control (LSMC)**: Sliding surface $s = \dot{e} + c_1 e$ with parameters $c_1 = 2$, $k_1 = 4$, $k_2 = 4$, $k_3 = 2$, $k_4 = 2$, $\alpha = 2$, $\beta = 0.5$.
- **PID Controller**: $P_{PID} = 60$, $I_{PID} = 1$, $D_{PID} = 3$ for proportional, integral, and derivative gains respectively.

Simulation results are shown in Figures 2 [Figure 2: see original paper] and 3 [Figure 3: see original paper].

The angle displacement and velocity tracking curves in Figure 2 show that PID control consistently deviates from the reference signal and fails to track accurately, with a tendency to drift further after disturbance injection. Among the three sliding mode controls, LSMC exhibits the longest convergence time due to the asymptotic convergence characteristic of its linear sliding surface, showing small deviations after disturbance injection. Both STTSMCDO and FXSMC demonstrate good tracking performance, with the variable exponential coefficient sliding surface enabling rapid reference signal tracking within finite time and robustness against disturbances. Compared with FXSMC, STTSMCDO's sliding surface includes an additional linear term that maintains fast convergence speed even when system states approach the equilibrium point. Additionally, FXSMC exhibits significant jitter during the first second of angular velocity tracking.

Table 1 presents the performance indices for sinusoidal signal tracking across the four control algorithms, showing that STTSMCDO offers advantages in settling time and root mean squared error (RMSE) for both angular displacement and angular velocity tracking.

The control input curves in Figure 3 [Figure 3: see original paper] reveal that among the four algorithms, PID control produces the smoothest curve due to its continuous input signal. The other three sliding mode controls exhibit fluctuations because sliding mode control uses high-frequency switching to make system states approximately slide on the sliding surface before finally stabilizing at the origin. FXSMC shows the most pronounced chattering, consistent with its first-order variable exponential coefficient reaching law, which, while robust, requires large control inputs. STTSMCDO and LSMC control algorithms produce input peaks only during direction reversal, with chattering well suppressed during unidirectional operation. However, LSMC's smaller control input also results in poorer overall dynamic performance. With the same control input, STTSMCDO employs a disturbance observer that reduces control magnitude, and the variable-gain super-twisting switching control law adjusts gains according to disturbances, making the control input smoother through its inherited second-order filtering characteristics and effectively suppressing chattering.

In summary, the designed variable exponential coefficient sliding surface (7) not only improves system state response speed but also ensures sufficient tracking accuracy and system stability. The switching control law (9) employs a variable-gain super-twisting algorithm that enables rapid and stable convergence under disturbances, with variable gains offering advantages over traditional fixed gains and effectively reducing chattering generation. Simulation experiments demonstrate that the proposed finite-time stable super-twisting terminal sliding mode controller based on a disturbance observer can track reference signals in approximately 0.55 seconds for antenna servo control systems, with system states converging to the origin within finite time, minimal tracking error RMSE, and improved robustness and chattering suppression through the super-twisting algorithm and disturbance observer. Therefore, this method offers advantages in short convergence time, high control precision, and strong anti-interference capability.

3.3 Wind Load Experiment

Wind load disturbance is the primary external interference affecting large antenna pointing and tracking accuracy. Wind load consists of mean load (or static load) and variable load (gust). The torque magnitude exerted by wind on the antenna depends on the antenna's geometry, orientation relative to wind direction, and wind characteristics. Mean wind load can be considered as a fixed or slowly varying torque, while the gust component is a random process. The Davenport wind speed spectrum is commonly used in antennas, where the random torque on the telescope axis is proportional to random wind speed and satisfies:

$$T_{\text{wind}} = c_t \alpha_p \pi D^3 \nu_m^2 \Delta\nu_0,$$

where c_t is the wind direction conversion coefficient, α_p is static air density, N_P is the gear ratio, ν_m is static wind speed, and $\Delta\nu_0$ is the unit scale of the wind speed model.

The wind load simulation experiment applies random torque to the antenna using the above method, with reference position command $x_d = \sin(t)$. The controller uses equations (8)-(11), the observer uses equation (4), and parameters are selected as $c_1 = 2$, $c_2 = 9$, $\sigma = 2$, $\mu = 0.1$, $h_3 = 2$, $k_1 = 5000$, $k_2 = 500$, $c_t = 0.25$, $\alpha_p = 0.613\,\mathrm{N} \cdot \mathrm{s}^2 \cdot \mathrm{m}^{-4}$, $D = 50\,\mathrm{m}$, $\nu_m = 5\,\mathrm{m} \cdot \mathrm{s}^{-1}$. Simulation results are shown in Figures 4 [Figure 4: see original paper] and 5 [Figure 5: see original paper].

The position and velocity error curves in Figure 4 demonstrate that STTSMCDO, with its disturbance observer, better suppresses adverse effects caused by random wind loads. Table 2 shows the RMSE values of angular displacement and velocity errors, proving that STTSMCDO with the disturbance observer achieves significantly improved tracking accuracy, with pointing RMSE reduced by more than half compared to STTSMC without the observer. The random wind load observation curve in Figure 5 shows that the disturbance observer can effectively estimate external random wind load torque, allowing the controller to compensate for the estimated wind load torque and improve robustness and dynamic performance.

4 Conclusion

For large-aperture telescope antenna servo systems with disturbances, this paper proposes a finite-time stable super-twisting terminal sliding mode controller based on a disturbance observer. A robust controller with finite-time convergence is designed using a state-dependent variable exponential coefficient sliding surface for fixed-time stability and a variable-gain super-twisting control law. Stability analysis and convergence time bound calculation are performed using the Lyapunov method. Simulation results verify the theoretical analysis of the STTSMCDO method. Compared with commonly used PID, LSMC, and FXSMC control methods, the proposed method demonstrates superiority and feasibility in convergence time, control precision, chattering suppression, and anti-interference capability. This method can be used to improve the dynamic performance indicators and robustness of antenna servo systems and provides a reference for high-precision pointing control of the Xinjiang Qitai 110-meter fully steerable radio telescope (QTT).

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Note: Figure translations are in progress. See original paper for figures.