Finite-time sliding mode control for model-free nonlinear systems with adaptive disturbance bound estimation

Nguyen Quang Binh, Vu Quoc Huy*

Control, Automation in Production and Improvement of Technology Institute/Academy of Military Science and Technology, 89B Ly Nam De, Hoan Kiem, Hanoi, Vietnam.

*Corresponding Email: maihuyvu@gmail.com

Received 03 Mar. 2026; Revised 24 Apr. 2026; Accepted 11 May 2026; Published 25May 2026.

DOI: https://doi.org/10.54939/1859-1043.j.mst.111.2026.3-11

ABSTRACT

This paper proposes a finite-time sliding mode controller for model-free SISO nonlinear systems within the framework of model-free control. Unlike previous studies that primarily focused on asymptotic stability and required prior knowledge of the upper limit of the disturbance, the proposed method uses a power approach law to achieve finite-time convergence, while simultaneously constructing an attenuated online adaptive disturbance amplitude estimation mechanism. This eliminates the requirement for prior knowledge of the disturbance bound in controller design and avoids the phenomenon of unlimited gain. The stability of the closed-loop system is demonstrated through a non-smooth Lyapunov function, establishing practical finite-time stability conditions and ISS robustness against slowly varying disturbances. The effectiveness of the method is verified through simulations on a standard nonlinear system with strongly nonlinear dynamics and a reference signal with breakpoints. The results show that the proposed controller significantly improves convergence speed, reduces integration errors (ISE, ITAE), and limits control vibration compared to traditional MFC-iPID and SMC controllers.

Keywords: Model-free control; Sliding mode control; Time-finite; Adaptive decay; ISS.

1. INTRODUCTION

Model-Free Control (MFC), proposed by Michel Fliess and Cédric Join [1], has opened a new approach in nonlinear control by using an ultra-local model instead of a full dynamic model. The term "ultra-local" emphasizes that the model is only valid for a very short period of time and is continuously updated online, thus avoiding the need to describe the system globally. This approach has been successfully applied to the electromechanical system in [2], showing good tracking capability and simplicity in implementation. In parallel, variable structure control and power approach law developed by Weiping Gao and Jin-Cheng Hung [3] allow for faster convergence and improved robustness against disturbances.

Recent studies by Radu-Emil Precup et al. [4–6] have combined MFC and SMC in the MFAC-SMC structure. However, most of these works only ensure asymptotic stability. Tight sliding mode structures with exponential approach law and fixed interference suppression are analyzed in [7], but still require prior knowledge of the interference boundary. The data-driven, model-free adaptive sliding mode control method in [8] allows for online updating of the interference compensation coefficient, but the monotonically increasing adaptive law can lead to prolonged overestimation.

In high-precision military applications such as target-tracking servos, radar platform stabilizers, or guidance systems, the requirement for fast convergence within a finite time and limiting control vibration is particularly important. Therefore, a control structure is needed that ensures convergence within a finite time, does not require prior knowledge of the upper interference boundary, avoids excessively increasing adaptive parameters, and has a tight stability proven according to the extended Lyapunov and ISS.

This paper proposes a finite-time sliding mode control structure in a model-free control framework with a two-stage adaptive disturbance boundary estimation law with attenuation. The proposed structure does not require prior knowledge of the disturbance bound, but also overcomes the unlimited gain increase of traditional adaptive laws. The stability of the closed-loop system is demonstrated using an extended Lyapunov function, while establishing conditions to ensure practical finite-time stability and ISS for slowly varying disturbances.

2. PROBLEM MODEL AND STATEMENT

Consider the SISO nonlinear system whose exact physical model is unknown, represented as an ultra-local model (1):

$$\dot{y}(t) = F(t) + \alpha \cdot u(t) \tag{1}$$

In there:

- $y(t)$: The output.
- $u(t)$: The control signal.
- $F(t)$: The combined dynamic component including unknown elements and external noise.
- $\alpha > 0$: An unknown parameter, but can be chosen by the designer.

The representation (1) originates from the principle of the ultra-local model in model-free control proposed in [1], where the entire unknown dynamics and disturbances are grouped into a composite component $F(t)$. In [2], the MFC-iPID structure has shown that online estimation of this component allows for good tracking quality for the electromechanical system. However, when $F(t)$ varies rapidly or contains a disturbance component that does not match the model, the estimation error can affect closed-loop stability. Therefore, this paper combines the ultra-local model structure [1, 2] with a robust disturbance compensation mechanism based on the sliding mode principle [3].

Unlike the model-based approach, within the MFC framework, $F(t)$ does not need to be explicitly known but is estimated online through measurement data. A simple discrete estimate can be constructed as (2):

$$\hat{F}(k) = \frac{y(k) - y(k-1)}{T} - \alpha \cdot u(k-1) \tag{2}$$

where T is the sampling period.

Remark 1: At each time t, the system is very complex, but we approximate it instantaneously with a purely mathematical system of the form (1). After a very small time interval, we will update $F(t)$. Therefore, (1) is called an ultra-local model. It does not describe every state of the system, but it accurately describes the system in a small neighborhood over time. Because the ideal reaching law contains a discontinuous sign term, the closed-loop trajectories are understood in the Filippov sense. In numerical implementation, the sign function is replaced by a saturation function to reduce chattering.

Assumption:

A1: $F(t)$ is bounded: $|F(t)| \leq D(t)$

A2: $D(t)$ is finite and varies slowly: $\left|\dot{D}(t)\right| \leq \delta$

Control problem: Design a control law $u(t)$ such that the tracking error converges to 0 within a finite time interval $D(t)$ without prior knowledge. The tracking error is defined as $e(t) = y(t) - yd(t)$, where $y(t)$ is the measured output and $y_d(t)$ is the reference signal.

3. CONTROLLER DESIGN

To achieve the stated goal, a nonlinear sliding surface (3) is constructed:

$$s = \dot{e} + \lambda |e|^{\gamma} \operatorname{sgn}(e) \tag{3}$$

With $0 < \gamma < 1; \lambda > 0$.

This type of sliding surface belongs to the class of nonlinear sliding surfaces that ensure time-finite convergence, developed from the principle of variable structure control in [3] and later extensions of the power approach law. Compared with traditional linear sliding surfaces used in previous MFAC-SMC structures [4–6], the nonlinear form allows for increased convergence speed near the origin. This structure ensures the deviation dynamics on the nonlinear sliding surface leading to time-finite convergence:

$$\dot{e} = -\lambda|e|^{\gamma}\text{sgn}(e) \tag{4}$$

Derivative of a sliding surface:

$$\dot{s} = \frac{d}{dt}\left(\dot{e} + \lambda|e|^{\gamma}\text{sgn}(e)\right) \tag{5}$$

When designing the control, we directly force the s dynamics according to the power reaching law (6):

$$\dot{s} = -k_1|s|^{\rho}\text{sgn}(s) - k_2 s \tag{6}$$

This reaching law is based on the foundational work of Gao and Hung [3], and has been used in tight sliding structures with noise suppression in [7]. However, studies [3, 7] assume a known upper limit of noise, while this paper rejects that assumption through a weakened adaptive mechanism.

To suppress unwanted components, a control law (7) is proposed:

$$u = \frac{1}{\alpha}\left(-\hat{F} + \dot{y_d} - \lambda|e|^{\gamma}\text{sgn}(e) - k_1|s|^{\rho}\text{sgn}(s) - k_2 s - \hat{D}\text{sgn}(s)\right) \tag{7}$$

Where, $k_1, k_2 > 0$, $0 < \rho < 1$, and $\hat{D}$ is an estimate of the disturbance margin.

To avoid the requirement of knowing the noise boundary beforehand, an adaptive attenuation law (8) is proposed:

$$\dot{\hat{D}} = \rho_1|s| - \rho_2\hat{D} \tag{8}$$

In model-free adaptive sliding mode control structures like [8], the disturbance compensation coefficient is usually updated according to a monotonically increasing law of error. This approach ensures robustness but is prone to prolonged overestimation. Unlike [8], this paper adds a decay component proportional to the estimate amplitude itself, creating a dynamic balancing mechanism between gain increase and decrease, thereby avoiding infinite increase, limiting control vibration, and is suitable for high-precision servo systems as investigated in [7].

4. STABILITY ANALYSIS

In [3], stability is proven based on a second-order Lyapunov function with the assumption that the disturbance is bounded by a known constant. In [7], the tight sliding structure also requires a predefined disturbance-bounding condition. Unlike the above works, this paper does not assume a known D_{max} but allows $D(t)$ to vary slowly, using an extended Lyapunov with an additional adaptation variable. The stability analysis below establishes the finite-time and ISS stability conditions for the closed-loop system. Because the reaching law contains a discontinuous sign term, the closed-loop solutions are understood in the Filippov sense. In implementation, $\text{sgn}(.)$ is replaced by $\text{sat}(.)$ within a thin boundary layer to reduce chattering.

4.1. Finite time convergence

Theorem 1. *Consider the closed system (1) with Assumption A1. With sliding surface (3), control law (7), and adaptation law (8), there exist constants $c_1, c_2 > 0$ such that:*

$$\dot{V} \le -c_1 V^{\alpha} + c_2 \tag{9}$$

In that case, the system is stable for a finite amount of time.

Proof:

According to the control design principle, the step-down form of the closed-loop system has the form (10):

$$\dot{s} = -k_1|s|^{\rho}\text{sgn}(s) - k_2 s + \widetilde{D} \tag{10}$$

With $\widetilde{D} = D - \widehat{D}$.

Select Lyapunov extension (11):

$$V = \frac{1}{2}s^2 + \frac{1}{2\rho_1}\left(\widetilde{D}\right)^2 \tag{11}$$

Take the derivative:

$$\dot{V} = s\dot{s} + \frac{1}{\rho 1}\widetilde{D}\dot{\widetilde{D}} \tag{12}$$

After detailed modifications:

$$\dot{V} = s\left(-k_1|s|^{\rho}\text{sgn}(s) - k_2 s + \widetilde{D}\right) + \frac{1}{\rho_1}\widetilde{D}\left(\dot{D} - \dot{\widehat{D}}\right) \tag{13}$$

After simplification, we obtain:

$$\dot{V} = -k_1|s|^{\rho+1} - k_2 s^2 + s\widetilde{D} + \frac{1}{\rho_1}\widetilde{D}\left(\dot{D} - \rho_1|s| + \rho_2\widehat{D}\right) \tag{14}$$

$$\dot{V} = -k_1|s|^{\rho+1} - k_2 s^2 + \widetilde{D}(s - |s|) + \frac{1}{\rho_1}\widetilde{D}\dot{D} + \frac{\rho_2}{\rho_1}\widetilde{D}\widehat{D} \tag{15}$$

According to Assumption A1, we have $\left|\dot{D}\right| \leq \delta$. Using Young's inequality (16):

$$\left|s\widetilde{D}\right| \leq \frac{\epsilon}{2}s^2 + \frac{1}{2\epsilon}\widetilde{D}^2 \tag{16}$$

Thus, there exist c_1, c_2 such that:

$$\dot{V} \leq -c_1 s^{\rho+1} - c_3 s^2 - c_4\widetilde{D}^2 + c_2 \tag{17}$$

Since $V \sim \left(s^2 + \widetilde{D}^2\right)$, therefore:

$$\dot{V} \leq -c_1 V^{\frac{\rho+1}{2}} + c_2 \tag{18}$$

According to the finite-time real-world stability theory, the system converges in time T:

$$T \leq \frac{V(0)^{\frac{1-\rho}{2}}}{\frac{c_1(1-\rho)}{2}} \tag{19}$$

The theorem has been proved.

■

4.2. ISS stability

Theorem 2. *Consider a closed-loop system with slowly varying noise satisfying Assumption A2. Then the closed-loop system is ISS with respect to the disturbance $\dot{D}(t)$, meaning there exist class functions $\mathcal{KL}$ and $\mathcal{K}$ such that:*

$$|s(t)| \leq \beta(|s(0)|, t) + \gamma(\delta) \tag{20}$$

Where β is the time-convergent fraction, and $\gamma(\delta)$ is the noise effect fraction; $\gamma(\cdot) \in \mathcal{K}$ if $\gamma: [0, \infty) \to [0, \infty)$ is continuous, strictly increasing function and $\gamma(0) = 0$; $\beta(\cdot,\cdot) \in \mathcal{KL}$ if with every $t \geq 0$, $\beta(\cdot, t) \in \mathcal{K}$, and with every $r \geq 0$, $\beta(r, t) \to 0$ when $t \to \infty$.

Proof:

According to Theorem 1, from (18) we have:

$$\dot{V} \le -c_1 V^{\alpha} + c_2 \tag{21}$$

With $0 < \alpha < 1$ and $c_2 = k\delta$

In the case where the system is free from noise: $\delta = 0$

$$\dot{V} \le -c_1 V^{\alpha} \tag{22}$$

This implies a finite-time convergence system T:

$$V(t) = 0 \ after \ T < \infty$$

In the case of a noisy system: $\delta \ne 0$

When: $c_1 V^{\alpha} > c_2 \Rightarrow \dot{V} < 0$, this means the system is being pulled back to the set.:

$$V \le \left(\frac{c_2}{c_1}\right)^{1/\alpha} \tag{23}$$

Since $V \sim s^2$, therefore:

$$|s| \le C_1 e^{-C_2 t} + C_3 \delta^{1/\alpha} \tag{24}$$

Thus (20) has the form (24). The system is ISS.

The theorem has been proved.

■

Remark 2: The ISS property implies that tracking performance degrades gradually and gently with the rate of change of the noise. Specifically, with constant noise, perfect convergence within a finite time is restored, while slowly changing noise causes only a small, limited steady-state error.

5. SIMULATION AND DISCUSSION

5.1. Simulation parameters and object

Verification system used:

$$\dot{y} = -y^3 + \sin(t) + u \tag{25}$$

Within the framework of model-free control, the system (25) is rewritten as an ultra-local model (26), (27):

$$\dot{y}(t) = F(t) + \alpha \cdot u(t) \tag{26}$$

$$F(t) = -y^3 + \sin(t)\,; \alpha = 1 \tag{27}$$

In the simulation, $F(t)$ is not used directly but is estimated through a discrete differential estimator (28) and a low-pass filter (29) to reduce measurement noise. Here, $y(k)$ denotes a discrete sample of the output at the time $t = kT_s$, so $y(k) = y(kT_s)$.

$$F_{raw}(k) = \frac{y(k) - y(k-1)}{T_s} - \alpha \cdot u(k-1) \tag{28}$$

$$\hat{F}(k) = 0.9\hat{F}(k-1) + 0.1F_{raw}(k) \tag{29}$$

The initial reference signal $y_d^{raw}(t)$ is the segment function (30):

$$y_d^{raw}(t) = \begin{cases} \sin(0.5t): & t \le 8 \\ 1 & : \ 8 < t \le 12 \\ -0.5 & : \ 12 < t \le 16 \\ \sin(0.8t): & t > 16 \end{cases} \tag{30}$$

To avoid derivative interference, the signal is filtered through (31):

$$y_d(k) = 0.98y_d(k-1) + 0.02y_d^{raw}(k) \tag{31}$$

The simulation uses a first-order high-pass filter of the form (32), (33) to approximate the derivative, which helps reduce noise amplification and makes the system feasible in practice. Here,

$e(k)$ denotes the discrete tracking error at the time $t = kT_s$, which is determined from $e(k) = y(k) - y_d(k)$.

$$\dot{e}(k) = \frac{2}{\tau + T}\big(e(k) - e(k-1)\big) + \frac{\tau - T}{\tau + T}\dot{e}(k-1) \tag{32}$$

$$\dot{y_d}(k) = \frac{2}{\tau + T}\big(y_d(k) - y_d(k-1)\big) + \frac{\tau - T}{\tau + T}\dot{y_d}(k-1) \tag{33}$$

Then apply the saturation limit of the derivative (34). This value is chosen based on the expected maximum amplitude of signal variation in the simulation scenario, and to avoid unrealistic amplification of noise from the approximate differentiator.

$$\dot{e}, \dot{y}_d \in [-20, 20] \tag{34}$$

Updated law: $\dot{\hat{D}} = \rho_1|s| - \rho_2\hat{D}$ has a discrete form (35):

$$\hat{D}(k+1) = \hat{D}(k) + T(\rho_1|s(k)| - \rho_2\hat{D}(k) \tag{35}$$

with condition (36):

$$\hat{D}(k) \geq 0 \tag{36}$$

The control law is implemented by using the $\text{sat}(\cdot)$ function (37) instead of the $\text{sgn}(\cdot)$ function to reduce chattering.

$$\text{sat}(s) = \frac{s}{|s| + \phi} \tag{37}$$

The control signal is limited according to (38) to ensure numerical feasibility:

$$u \in [-50, 50] \tag{38}$$

Simulation time: 20 seconds, sampling period: $T_s = 1\ ms$.

Table 1. *Parameters of the verification system and controller.*

$\boldsymbol{\lambda}$	$\boldsymbol{\gamma}$	$\boldsymbol{k_1}$	$\boldsymbol{k_2}$	$\boldsymbol{\rho_1}$	$\boldsymbol{\rho_2}$
5	0.5	25	10	30	1
$\boldsymbol{\tau}$	$\boldsymbol{\hat{F}(1)}$	$\boldsymbol{y_1(1)}$	$\boldsymbol{y_2(1)}$	$\boldsymbol{y_3(1)}$	$\boldsymbol{\hat{D}(1)}$
0.02	0	1.5	1.5	1.5	1.5
$\boldsymbol{K_P}$	$\boldsymbol{K_I}$	$\boldsymbol{K_D}$	$\boldsymbol{k_{smc}}$	$\boldsymbol{\phi}$	$\boldsymbol{\rho}$
8	5	0.1	15	0.2	0.6

5.2. Simulation results

Table 2. *Comparison of integration performance between controllers.*

Methods	IAE	ISE	ITAE	RMSE
Proposed	0.119	0.087	1.026	0.066
MFC-iPID [2]	1.481	0.582	14.234	0.171
SMC [4-6]	0.198	0.175	1.671	0.093

Table 2 shows that the proposed control structure achieved superior performance compared to the two comparative methods across all evaluation criteria. Specifically, the IAE index of the proposed method was only 0.119, approximately 12 times smaller than MFC-iPID and significantly lower than traditional SMC, indicating a marked improvement in overall tracking error. Similarly, the lowest ISE value (0.087) reflects the ability to suppress errors more quickly and effectively throughout the transient process. For the ITAE criterion, the proposed method achieved 1.026, much lower than MFC-iPID (14.234) and a further improvement over SMC, demonstrating that the error was reduced rapidly from the initial stage, consistent with the time-finite convergence characteristic. At the same time, the smallest RMSE (0.066) confirms highly stable tracking accuracy in the steady state. These results demonstrate that the combination of nonlinear sliding surfaces, power approach laws, and attenuation adaptation mechanisms significantly improves both convergence speed and control quality, effectively overcoming the limitations of traditional MFC-iPID and SMC methods.

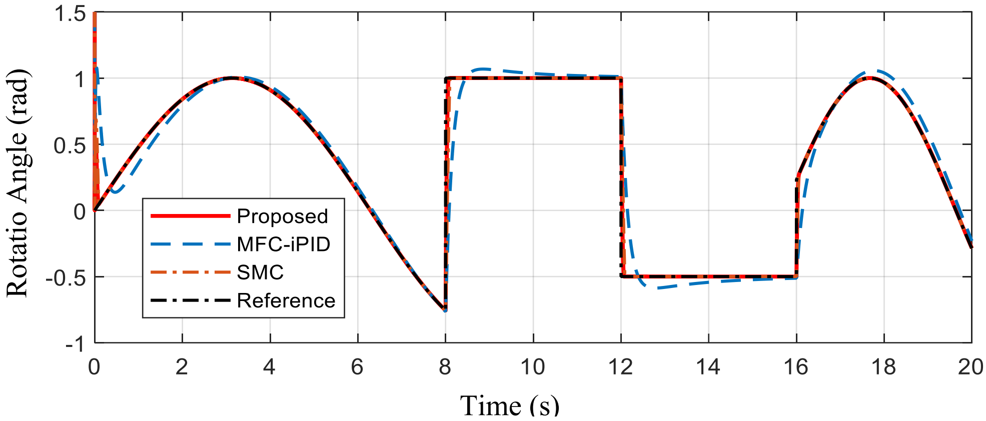

Figure 1. *Output signals between controllers.*

Figure 1 shows the output responses of three controllers: the proposed method, the MFC-iPID [1], and the MFAC-SMC structure [4-6]. Figure 1 shows that the proposed controller achieves the shortest settling time, consistent with the time-finite convergence proof in Theorem 1. Overshoot is almost negligible, demonstrating the effect of the nonlinear sliding surface and the power approach law. The MFC-iPID has a significantly slower transient response, consistent with the large ITAE index in Table 2. The traditional SMC converges faster than iPID but is still slower than the proposed method due to its asymptotically accurate response.

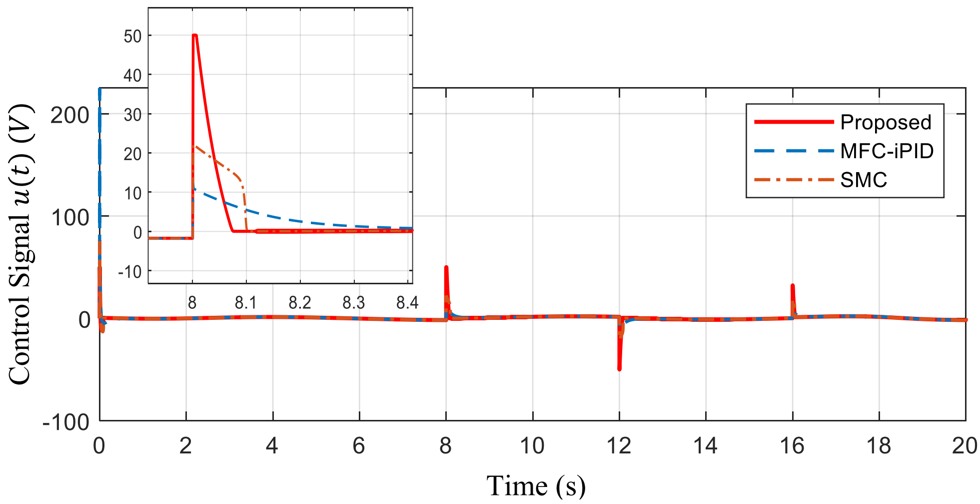

Figure 2. *Control signals between controllers.*

Figure 2 illustrates the amplitude and oscillation characteristics of the control signal. Observations show that traditional SMC exhibits large amplitude oscillations (chattering), while MFC-iPID has a smooth signal, but the amplitude is maintained for a long time due to slow convergence. The proposed method produces a control signal with a smaller amplitude than SMC, rapidly decreasing to a stable value, and without prolonged gain increase. This demonstrates that the attenuation adaptation mechanism has overcome the overestimation of the adaptation coefficient, which is often encountered in structures such as adaptive SMC.

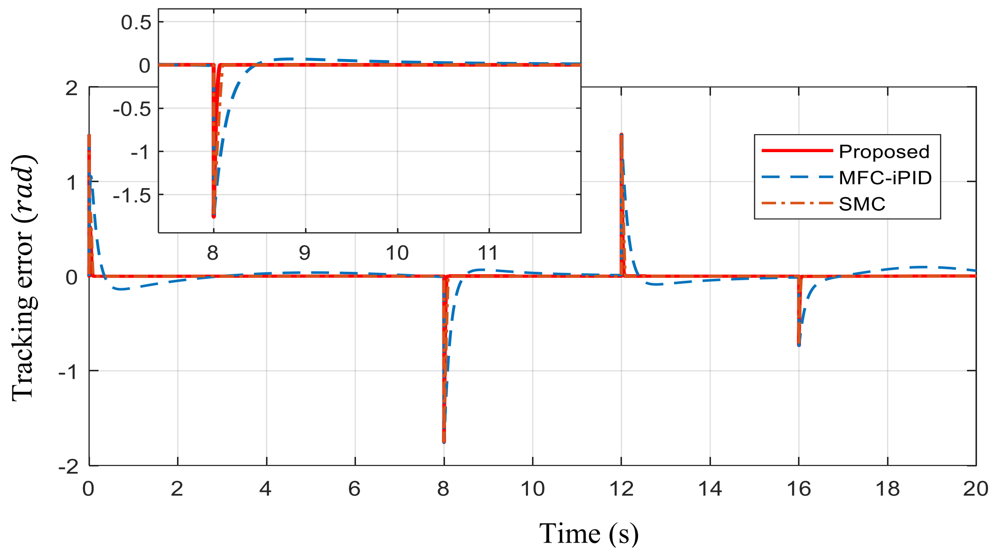

Figure 3. *Tracking error between controllers.*

Figure 3 directly illustrates the bias dynamics. From the graph, it can be seen that the bias of the proposed method decreases to near zero within a clearly finite time interval. Traditional SMC tends to converge asymptotically, while MFC-iPID has a longer convergence tail, and notably, the bias does not exhibit large high-frequency oscillations, nor does it have a small error extension region like iPID. This is consistent with the ISS analysis in Theorem 2: When the noise varies slowly, the system converges to a small neighborhood that is blocked.

Remark 3: The three figures along with the IAE, ISE, ITAE, and RMSE indices in Table 2 show that the proposed controller offers faster convergence speed, smaller bias, less oscillating control signals, and no prolonged adaptive gain increase. This indicates that the attenuated adaptive mechanism has resolved the classic conflict between fast convergence and control amplitude reduction.

6. CONCLUSIONS

This paper proposes a finite-time sliding mode control architecture within the framework of model-free control for uncertain SISO nonlinear systems. The method combines an ultra-local model, a power approach law, and an attenuated adaptive disturbance amplitude estimation mechanism; thereby, it does not require prior knowledge of the disturbance bound in designing and stability analysis, and limits the phenomenon of unlimited gain increase. Unlike traditional MFAC-SMC architectures, the proposed method establishes realistic finite-time stability conditions and ISS for slowly varying disturbances through extended Lyapunov analysis. Simulation results show significant improvements in convergence speed, tracking accuracy, and control amplitude reduction.

In the future, the method can be extended to multivariable systems, incorporating disturbance observers and experimental verification on real systems. This is an effective approach for uncertain nonlinear systems requiring fast response and high robustness.

REFERENCES

[1]. M. Fliess and C. Join, *"Model-free control and intelligent PID controllers: Towards a possible trivialization of nonlinear control?"*, IFAC Proceedings Volumes, Vol. 42, No. 10, pp. 1531-1550, (2009).

[2]. Nguyễn Văn Đức, Nguyễn Quang Hùng, and Vũ Quốc Huy, *"Model-Free Data-Driven Control MFC-IPID for a Class of Electro-Mechanic Systems"*, Journal of Military Science and Technology, no. FEE, pp. 50-57, (2022).
[3]. W. C. Gao and J. C. Hung, *"Variable structure control of nonlinear systems: A new approach"*, IEEE Trans. Ind. Electron., Vol. 40, pp. 45-55, (1993).
[4]. R.-E. Precup, M.-B. Radac, E. M. Petriu, C.-A. Dragos, and S. Preitl, *"Model-free tuning solution for sliding mode control of servo systems"*, in Proc. 8th Annual IEEE International Systems Conference, Ottawa, ON, Canada, pp. 30-35, (2014).
[5]. R.-E. Precup, M.-B. Radac, and R.-C. Roman, *"Model-free sliding mode control of nonlinear systems: Algorithms and experiments"*, Information Sciences, Vol. 381, pp. 176-192, (2017).
[6]. R.-E. Precup, R.-C. Roman, E.-L. Hedrea, E. M. Petriu, and C.-A. Dragos, *"Data-driven model-free sliding mode and fuzzy control with experimental validation"*, International Journal of Computers, Communications & Control, Vol. 16, No. 1, pp. 1-17, (2021).
[7]. Quoc Huy Vu, *"Strict Sliding Mode Control with Power Reaching Law and Disturbance Bounds in Synchronous Servo Tracking Drive System"*, International Journal of Electrical and Electronic Engineering & Telecommunications, Vol. 12, No. 5, pp. 350-357, (2023).
[8]. X. Wang, X. Li, J. Wang, X. Fang, and X. Zhu, *"Data-driven model-free adaptive sliding mode control for the multi-degree-of-freedom robotic exoskeleton"*, Information Sciences, Vol. 327, pp. 246-257, (2016).

TÓM TẮT

Điều khiển trượt thời gian hữu hạn cho hệ phi tuyến phi mô hình với ước lượng giới hạn nhiễu thích nghi

Bài báo đề xuất một cấu trúc điều khiển trượt thời gian hữu hạn cho hệ phi tuyến SISO không biết mô hình trong khuôn khổ điều khiển phi mô hình. Khác với các nghiên cứu trước đây chủ yếu đảm bảo ổn định tiệm cận và yêu cầu biết trước chặn trên của nhiễu, phương pháp đề xuất sử dụng luật tiếp cận lũy thừa để đạt hội tụ thời gian hữu hạn, đồng thời xây dựng cơ chế ước lượng biên nhiễu thích nghi trực tuyến có suy giảm, qua đó loại bỏ yêu cầu phải có kiến thức trước về giới hạn của nhiễu trong thiết kế bộ điều khiển và tránh hiện tượng tăng độ lợi không giới hạn. Tính ổn định của hệ kín được chứng minh thông qua hàm Lyapunov không trơn, thiết lập điều kiện ổn định hữu hạn thời gian thực tế và tính bền vững ISS đối với nhiễu biến thiên chậm. Hiệu quả của phương pháp được kiểm chứng thông qua mô phỏng trên hệ phi tuyến chuẩn với động học không tuyến tính mạnh và tín hiệu tham chiếu có điểm gãy. Kết quả cho thấy, bộ điều khiển đề xuất cải thiện rõ rệt tốc độ hội tụ, giảm sai số tích phân (ISE, ITAE) và hạn chế rung điều khiển so với các cấu trúc MFC-iPID và SMC truyền thống.

Từ khoá: Điều khiển phi mô hình; Trượt hữu hạn thời gian; Thích nghi biên nhiễu; Hệ phi tuyến SISO; Điều khiển bền vững.