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Variable-parameter double-power reaching law sliding mode control method*

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ABSTRACT
To solve the problem of the slow convergence rate of the reaching law and the chattering problems in the dynamic response in the sliding mode control, an improved double-power sliding mode reaching law is proposed. The reaching law is adjusted by changing the magnitude of the power terms adaptively at different stages of the system approach process, and the convergence speed of the dynamic response process is greatly improved. Its existence, accessibility and stability are proven by theory. The simulation results show that the improved double-power reaching law is faster than the double-power reaching law and the fast power reaching law. When there is uncertainty in the system, the system state and its derivatives can rapidly converge to the neighbor-hood of the equilibrium zeros. In the presence of time-varying perturbations of the two-order system, the sliding mode control system based on the improved double-power sliding mode reaching law has higher tracking precision of the given signal and differential signal and effectively reduces the high-frequency chattering phenomenon of the control input signal.

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Sliding mode control; reaching law; power term function; approach speed; uncertain system

1. Introduction

Sliding mode control (SMC) is a systematic and effective robust control approach to maintain the system stability and consistent performance in the presence of modeling uncertainties and disturbances. SMC is widely applied to various uncertain systems due to its ideal robustness. The sliding mode control consists of two processes: reaching motion and sliding mode motion. In the approaching stage, the sliding mode control system is affected by parameter uncertainties and external disturbances. Therefore, a research hotspot is the method to speed up the convergence rate of the approaching phase, ensure the tracking accuracy of the given signal under disturbance and suppress the chattering of the control variables in the process.

The reaching law can improve the dynamic performance of the approaching motion. The fundamental design procedure of the SMC is to properly design a stable sliding surface, which satisfies the desired specifications, and select a feedback control law such that the sliding surface can be reached and retained in the sense of Lyapunov despite the presence of modeling uncertainties and disturbances. An extended state observer (ESO)-based SMC method is designed to deal with mismatched disturbances in ref. [1]. A new switching type reaching law for sliding mode control of discrete-time systems is proposed in ref. [2], the proportional term is modified, so that the rate is always bounded. In ref. [3], a multi-power reaching law of sliding mode control is proposed in this paper, which aims at reducing chattering phenomenon, fastening convergence speed and making dynamic process smoothly. In ref. [4], a novel approach to the design of reaching law based on SMC for multi-input multi-output (MIMO) non-linear systems so as to overcome the drawbacks associated with conventional reaching law based SMC design strategies. In ref. [5], a new reaching law for sliding mode control is constructed by using a special power function and an inverse hyperbolic sinusoidal function, and an adaptive sliding mode control law is designed using this reaching law. The asymptotic convergence property of the sliding mode control system error is proven. Ref. [6] uses an exponential function to design a nonlinear reaching law. The exponential function can dynamically adapt to the change of the controlled system, reduce the jitter of the control input, and maintain the high tracking performance of the controller in the steady-state. The sliding mode control method based on the fast double-power reaching law is used to realize the asymptotic tracking of the position and velocity signals in ref. [7], which overcomes the disadvantage of serious chattering caused by the traditional sliding mode control

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reaching law. A generalized discrete-time reaching law for sliding variables with arbitrary relative degree is proposed in ref. [8], the reaching law is based on Gao's strategy and ensures higher-order switching type sliding motion, which is a novel concept in the field of discrete-time plants. To avoid the chattering problem in the reaching-law-based discrete-time sliding mode control (DSMC) and the generation of over-large control action in the equivalent-control-based DSMC, a new DSMC method based on non-smooth control is proposed in ref. [9]. In ref. [10], a sliding mode reaching law is constructed, which can drive the state trajectory to the specified sliding surface within a specified finite time interval. By introducing the partitioning strategy, the boundedness of finite time is guaranteed at the arrival stage and sliding mode stage. The generalized reaching law is proposed in ref. [11]. The proposed reaching law in ref. [12] eliminates undesirable chattering, and ensures that the sliding variable rate of change is upper bounded by a design parameter which does not depend on the system initial conditions. Ref. [13] presents a two-power reaching law with second-order sliding mode characteristics and finite-time convergence, which is verified by simulation in the attitude control of a flying-wing UAV with complex disturbances. Ref. [14] presents an adaptive reaching law sliding mode controller, which is verified by simulation in a double-shaking-table system with parameter uncertainties and disturbances. The SMC has been successfully applied in the permanent-magnet synchronous motor [15] and steer-by-wire system in vehicles [16]. A control structure to solve the tracking problem in a class of uncertain mechanical systems is proposed in ref. [17]. The numerical simulations and real-time experiments carried out in a mass-spring-damper system show the performance and effectiveness of the control structure.

However, the isokinetic reaching law has the following problems: slow approach speed and single approaching speed. The exponential reaching law has a larger chattering phenomenon when approaching the sliding mode. The power reaching law has a relatively low approaching rate in the approaching state of the state away from the sliding mode. To weaken the chattering phenomenon of the input signals of the sliding mode control and improve the sliding mode approaching rate, a sliding mode control method with the variable-parameter double-power reaching law is proposed in this paper. First, the reachability, existence and steady-state buffeting characteristics of the reaching law are analysed. Then, the approaching rate of the reaching law is compared and analysed. Finally, the sliding mode control method with the variable-parameter double-power reaching law is used to simulate a class of second-order nonlinear systems with uncertain time-varying disturbances.

2. Second-power convergence law of variable parameters and its characteristic analysis

2.1. Design of the double-power convergence law with variable parameters

For continuous-time systems, the double-power reaching law with variable parameters is designed as follows. When the state of the system is far away from the sliding mode $|s| > 1$:

$$\dot{s} = -k_1|s|^{\alpha_1}\text{sgn}(s) - k_2|s|^{\alpha_2}\text{sgn}(s) \tag{1}$$

When the system state is near the sliding mode $|s| < 1$:

$$\dot{s} = -k_1|s|^{\beta 1}\text{sgn}(s) - k_2|s|^{\beta_2}\text{sgn}(s) \tag{2}$$

Among them: $\alpha_1 > 1, \alpha_2 > 1; 0 < \beta_1 < 1, 0 < \beta_2 < 1; k_1 > 0, k_2 > 0$. By adjusting the size of the power coefficient under different conditions of the system, the motion quality of the system state in the process of approaching the sliding mode is guaranteed.

2.2. Proof of existence and accessibility

Lemma 1. *For reaching law* (1) *and law* (2)*, the system state can reach the equilibrium point $s(0,0) = 0$ under its action. According to the continuous system sliding mode approach law exists and reachability conditions* [18], *which satisfied $s\dot{s} \leq 0$, then the designed sliding mode approach law exists, that is, the system states can reach the equilibrium point under the action of the approach law* (1) *and law* (2). *It is proven that the formula can be obtained according to formula* (1):

$$\begin{aligned} s\dot{s} &= -k_1|s|^{\alpha_1} \cdot s \cdot \text{sgn}(s) - k_2|s|^{\alpha_2} \cdot s \cdot \text{sgn}(s) \\ &= -k_1|s|^{\alpha_1+1} - k_2|s|^{\alpha_2+1} \leq 0 \end{aligned} \tag{3}$$

Based on formula (2), the relation can be obtained:

$$\begin{aligned} s\dot{s} &= -k_1|s|^{\beta_1} \cdot s \cdot \text{sgn}(s) - k_2|s|^{\beta_2} \cdot s \cdot \text{sgn}(s) \\ &= -k_1|s|^{\beta_1+1} - k_2|s|^{\beta_2+1} \leq 0 \end{aligned} \tag{4}$$

When and only when $s(0,0) = 0$, there is $s\dot{s} = 0$.

2.3. Steady-state buffeting analysis

For the variable-parameter double-power approach law(1) and law(2), because all the components of the formula contain s, when $s = 0^+$ and $s = 0^-$, formula(1) and formula(2) can be obtained by integration $\dot{s}(0^+) = \dot{s}(0^-) = 0$ as $\dot{s} = 0$, i.e. the system will not produce buffeting when it is near the steady-state.

2.4. Velocity analysis of the sliding mode reaching law

For law (1), state s and ds converge to the zero point in finite time, i.e. after the finite convergence time, the states are $s = \dot{s} = 0$.

According to the sliding mode reachability, combination law (1) and condition: $\alpha_1 > 1$, $\alpha_2 > 1$; $k_1 > 0$, $k_2 > 0$. Assuming that the initial state of the system is s(0), the finite-time t calculation is performed in 2 stages.

(1) s(0) > 1 near s = 1. At this point, because: $\alpha_1 > 1$, $\alpha_2 > 1$; $k_1 > 0$, $k_2 > 0$. The rate is affected by formula (1). Formula (1) is considered as:

$$\dot{s} = -k_1|s|^{\alpha_1}\text{sgn}(s) \tag{5}$$

$$\dot{s} = -k_2|s|^{\alpha_2}\text{sgn}(s) \tag{6}$$

The two equations are separately solved. In the case of (5) and (6), the approximate time required is solved. The specific process of solving formula (5) is as follows:

$$s^{-\alpha_1}\frac{ds}{dt} = -k_1 \tag{7}$$

The two sides of formula(7) are integrals, the required time for s(0) to approach s = 1 under formula(5) can be obtained:

$$t_1 = \frac{1 - s(0)^{1-\alpha_1}}{k_1(\alpha_1 - 1)} \tag{8}$$

Similarly, we can find the required time under formula (6):

$$t_{11} = \frac{1 - s(0)^{1-\alpha_2}}{k_2(\alpha_2 - 1)} \tag{9}$$

(2) s(0) = 1 near s = 0. At this point, because $0 < \beta_1 < 1, 0 < \beta_2 < 1; k_1 > 0, k_2 > 0$. the rate is affected by formula (2). Formula (2) is considered as:

$$\dot{s} = -k_1|s|^{\beta_1}\text{sgn}(s) \tag{10}$$

$$\dot{s} = -k_2|s|^{\beta_2}\text{sgn}(s) \tag{11}$$

The required time for s(0) = 1 to approach s = 0 under formula(10) can be obtained:

$$t_2 = \frac{1}{k_1(1 - \beta_1)} \tag{12}$$

The required time for s(0) = 1 to approach s = 0 under formula(11) can be obtained:

$$t_{21} = \frac{1}{k_2(1 - \beta_2)} \tag{13}$$

When the initial states $s(0) < -1$, it is also possible to calculate the time of convergence in the stages. The system state convergence time can be obtained.

2.5. Analysis of the stable boundary of the variable-parameter double-power reaching law

The lemma for uncertain systems is:

$$\dot{s} = -k_1|s|^{\alpha_1}\text{sgn}(s) - k_2|s|^{\alpha_2}\text{sgn}(s) + \text{d(t)} \tag{14}$$

$$\dot{s} = -k_1|s|^{\beta_1}\text{sgn}(s) - k_2|s|^{\beta_2}\text{sgn}(s) + \text{d(t)} \tag{15}$$

Suppose that $|d(t)| \leqslant \delta$, $\delta > 0$ is a positive number. The state of system (14) converges to the following regions in a limited time:

$$|s| \leq \min\left(\left(\frac{\delta}{k_1}\right)^{1/\alpha_1}, \left(\frac{\delta}{k_2}\right)^{1/\alpha_2}\right) \tag{16}$$

$$|\dot{s}| \leq \min\left(\delta, k_1\left(\frac{\delta}{k_2}\right)^{\alpha_1/\alpha_2}\right) + \min\left(\delta, k_2\left(\frac{\delta}{k_1}\right)^{\alpha_2/\alpha_1}\right) + \delta \tag{17}$$

The state of system (15) converges to the following regions in a finite time:

$$|s| \leq \min\left(\left(\frac{\delta}{k_1}\right)^{1/\beta_1}, \left(\frac{\delta}{k_2}\right)^{1/\beta_2}\right) \tag{18}$$

$$|\dot{s}| \leq \min\left(\delta, k_1\left(\frac{\delta}{k_2}\right)^{\beta_1/\beta_2}\right) + \min\left(\delta, k_2\left(\frac{\delta}{k_1}\right)^{\beta_2/\beta_1}\right) + \delta \tag{19}$$

In the application of the actual control system, the uncertainty can be estimated online by designing the disturbance state observer to eliminate the effect and guarantee the second-order sliding mode $s = \dot{s} = 0$.

2.6. The variable-parameter power term design for double-power reaching law

The double-power reaching law with variable-parameters power term function is redesigned as follows:

$$\dot{s} = -k_1|s|^{s\cdot\arctan(\frac{\pi}{2}\cdot s)}\text{sgn}(s) - k_2|s|^{s\cdot\arctan(\frac{\pi}{2}\cdot s)}\text{sgn}(s) \tag{20}$$

The power term in law (20) has the following characteristics:

(1) Because the definition domain of arctangent function is all real numbers, and it increases monotonously in (-∞, +∞) interval. So the power term $\arctan(\frac{\pi}{2} \cdot s)$ increases monotonously in (-∞, +∞) interval.

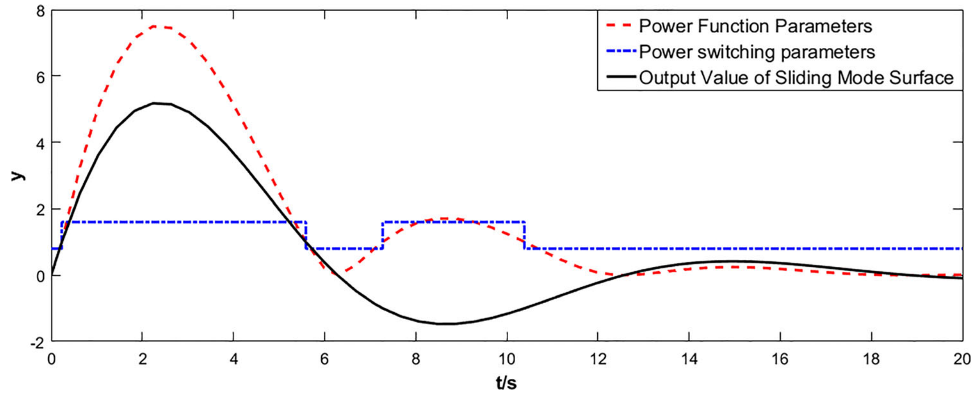

Figure 1. Comparison of the parameters of different power term function.

(2) When $s > 0$, $\arctan(\frac{\pi}{2} \cdot s) > 0$, and when $s < 0$, $\arctan(\frac{\pi}{2} \cdot s) < 0$, so the power term $s \cdot \arctan(\frac{\pi}{2} \cdot s)$ is constant greater than or equal to 0.
(3) Because the power term $\arctan(\frac{\pi}{2}) \to 1$, and when $|s| > 1$, $s \cdot \arctan(\frac{\pi}{2} \cdot s) > 1$, when $0 < |s| < 1$, $s \cdot \arctan(\frac{\pi}{2} \cdot s) < 1$, so the power function can adjust the power parameters adaptively under different conditions of the system. And the reaching law (20) has fast reaching speed both far away from and near sliding mode.

As $s \neq 0$, the power term function satisfies the conditions of the power parameters in Section A. Under different conditions of s, the parameters of the power term function proposed in this paper and the power term switching function are shown in Figure 1. When the sliding mode state $|s| > 1$, the switching function parameters only have a fixed value greater than 1, and the farther the sliding mode states s is away from the equilibrium state, the bigger the power term parameter values are, so the faster the sliding mode approaching speed is. When the sliding mode $0 < |s| < 1$, the switching function parameters are only fixed values less than 1 and more than 0, but the closer the sliding modes s is to the equilibrium state, the smaller the power term parameters are, so the variable-parameter sliding mode approaching speed is faster. Therefore, in the whole process of sliding mode approaching, the power term function of the variable-parameter approaching law can guarantee the adaptive adjustment of the power term parameters, thereby improving the approaching speed of sliding mode.

3. Simulation example and analysis

For the equation of state of the second-order system:

$$x = A\dot{x} + Bu \tag{21}$$

where:

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix},$$

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix},$$

$$B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix},$$

Thus, there is: $\dot{x}_2 = A_{21}x_1 + A_{22}x_2 + B_2 \cdot u + d(t)$. The sum of the internal and external disturbances of the system are included in d(t). And d(t) has a boundary: $|\,d(t)\,| \leqslant D$.

It is assumed that the set of inputs for the second-order system is r(t) and $\dot{x}_1 = x_2$. The errors are:

$$e = r(t) - x_1 \tag{22}$$

The error rate is:

$$\dot{e} = \dot{r}(t) - x_2 \tag{23}$$

The sliding mode function is:

$$s = c \cdot e + \dot{e} \tag{24}$$

Then, we have:

$$\dot{s} = c \cdot \dot{e} + \ddot{e} = Q_{slaw} \tag{25}$$

By substituting the equation of states (20) into formula (23), we find:

$$u = \frac{1}{B_2}[c(\dot{r} - x_2) + \ddot{r} - A_{21}x_1 - A_{22}x_2 - d(t) - Q_{slaw}] \tag{26}$$

3.1. Comparative simulation of the reaching laws

Nonlinear single-input single-output systems are considered:

$$\dot{s} = u + d(t) \tag{27}$$

d(t) is the uncertainty of the system. Assuming that the initial state of the system is d(t) = 0, and the initial value of the system is s(0) = 5. The fast single-power reaching law, double-power reaching law and variable-parameter double-power reaching law, which is proposed in this paper, are used to design the control law

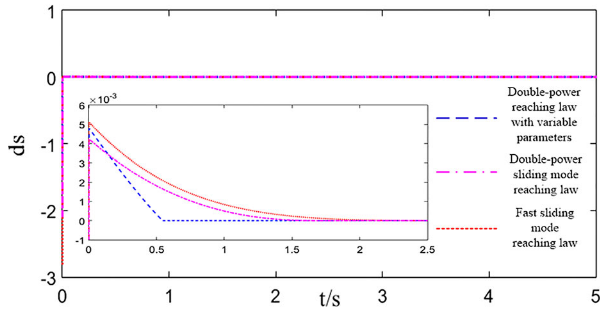

Figure 2. Comparison of the convergence speed of the sliding modes in different reaching laws.

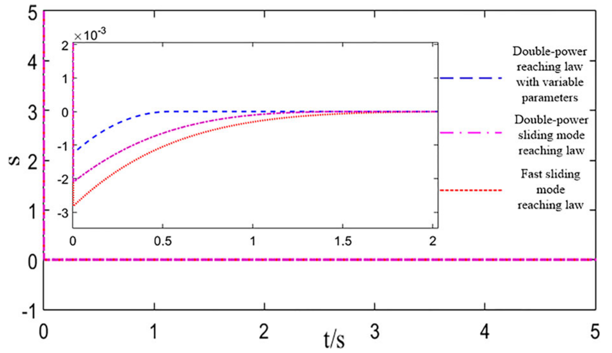

Figure 3. Comparison of the convergence rates of different reaching laws.

u, and a comparative simulation is performed. Sliding mode s and its first derivative convergence curve ds are shown in Figures 2 and 3.

Fast sliding mode reaching law:

$$\dot{s} = -k_1|s|^{\alpha_1}\text{sgn}(s) - k_2 s \tag{28}$$

Double-power sliding mode reaching law:

$$\dot{s} = -k_1|s|^{\alpha_1}\text{sgn}(s) - k_2|s|^{\alpha_2}\text{sgn}(s) \tag{29}$$

As illustrated in Figures 2 and 3, the fast power reaching law, double-power reaching law and variable-parameter double-power reaching law eliminate chattering in the steady state. The system states $\dot{s}$ converge to the steady-state bound error limit in 0.5×10^{-3}s. Figure 3 shows that when the system state is far away from the sliding mode, the rate of the double power approaching law proposed in this paper is higher than other approaches. When the system state is close to the sliding mode, the rate of the double power approaching law is lower than other approaching laws. The rate of the double power approaching law proposed in this paper achieves a smooth transition with the sliding mode, which is beneficial to weaken the system chattering. A larger initial error that corresponds to the speed advantage of the double-power reaching law with variable parameters is more obvious. The system states s converge to the steady-state bound error limit in a finite time less than 0.5×10^{-3}s and the variable-parameter double-power reaching law is the fastest.

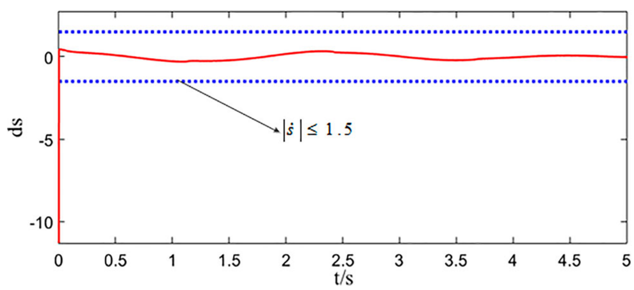

Figure 4. Convergence curves of ds and its steady-state error bounds under perturbation.

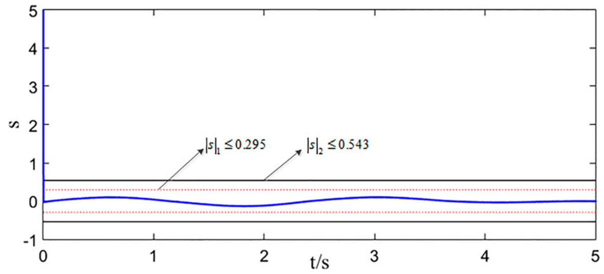

Figure 5. Convergence curves of s and its steady-state error bounds under perturbations.

3.2. *Steady-state error bound simulation of the variable-parameter double-power reaching law*

When the perturbation is $d(\text{t}) = 0.3\sin(3\text{t}) + 0.3\cos(2\text{t})$, based on the variable-parameter double-power reaching law (26), control law u is designed and simulated. The correctness of the test formula (16), (17), (18) and (19) is verified. The initial value of the system is s(0) = 5; in formula (1) and formula (2): order $\alpha_1 = 1.5$, $\alpha_2 = 1.6$; $\beta_1 = 0.75$, $\beta_2 = 0.8$;$k_1 = 1.5$, $k_2 = 0.8$. The parameters were substituted into (16) and (18), and we obtained: $|s|_1 \leq 0.295$, $|s|_2 \leq 0.543$. A substitution of formula (17) and formula (19) can obtain $|\dot{s}| \leq 1.5$.

The simulation results are shown in Figures 4 and 5. As illustrated in Figures 4 and 5, in the case of disturbance, system state s and $\dot{s}$ converge to the steady-state bound error limit in a finite time. The steady-state error does not exceed the result of formula formula(16), (17), (18) and (19). Moreover, system state s converges to its minimum steady-state error bounds in its entire sliding mode.

3.3. *Variable-parameter double-power reaching law sliding mode control simulation*

For equation of state (21):

$$A = \begin{bmatrix} 0 & 1 \\ 0 & -30 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 120 \end{bmatrix},$$

$$C = [350 \quad 1].$$

The given instruction r is a sinusoidal signal. Suppose the second-order system (21) is set to input a

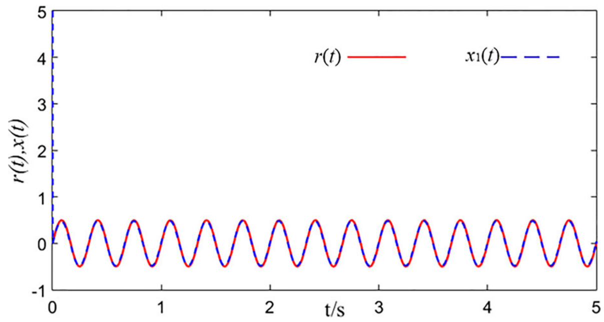

Figure 6. Tracking curve of a given signal.

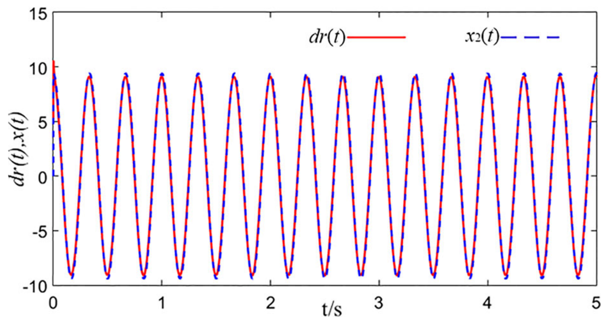

Figure 7. Tracking curve of a given differential signal.

signal: $r(\mathrm{t}) = 0.5\sin(2\mathrm{t})$, $d(\mathrm{t}) = 0.5\sin(2\pi\ \mathrm{t})$. The initial state of the system is not consistent with the initial value of the input signal. The system uses the variable-parameter double-power sliding mode control law(1) and law(2). Among them, take parameters $\alpha_1 = 1.5, \alpha_2 = 1.6; \beta_1 = 0.75, \beta_2 = 0.8; k_1 = 1.5, k_2 = 0.8$. A given signal tracking curve and a given differential signal tracking curve of the system are shown in Figures 6 and 7, respectively. The control input signal is shown in Figure 8. Figure 6 shows that the tracking accuracy of the given signal is high. The steady-state tracking error of the system is less than 0.01, when the initial state is $x_0 = [5,5]$. Figure 7 shows that the given differential signal has a higher tracking accuracy, and the steady-state tracking error is less than 0.26. With the increase of C in the sliding mode function (24), the tracking accuracy will be improved. Figure 8 shows that when the initial state is not 0, the amplitude of the input signal is rapidly reduced at the initial stage. After 0.002s, the absolute value is less than 2.5. Moreover, the sliding mode control reaching law(1) and law(2) effectively reduce the chattering phenomenon of the input signals.

4. Conclusion

In this paper, we propose a double-power reaching law, which can be pertinently adjusted by changing the power term adaptively at different stages of the system in the reaching process. Its existence, reachability and stability are proven. The simulation results show that the variable-parameter multi-power reaching law has faster convergence speed than the double-power reaching law and the fast power reaching law. In the case of

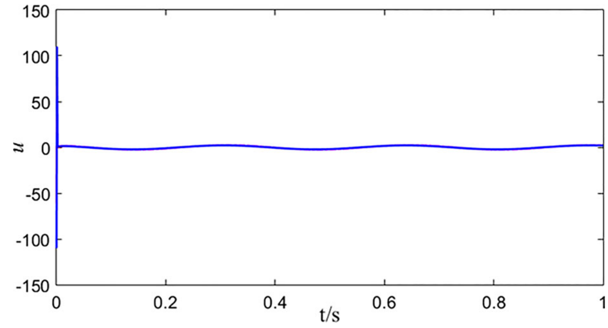

Figure 8. Curve of the control input signal.

uncertain time-varying perturbations, the system state and its derivatives can converge rapidly to the neighbourhood of the equilibrium zero. The sliding mode control system based on variable-parameter double-power sliding mode reaching law has higher tracking accuracy for given signal and given differential signal. It also effectively reduces the high-frequency buffeting phenomenon of control input signal. In this publication, we show that numerical experiment has higher tracking precision of given signal and given differential signal and effectively reduced the high-frequency buffeting phenomenon of control input signal.

The new sliding mode control approaching law is simple in structure, and the effect of suppressing the chattering phenomenon of the sliding mode control input signal is obvious. When the parameters satisfy the certain relationship between the parameters in the proposed double-power approach law, the system's interference stability boundary will be reduced. The system has better anti-interference ability, can be applied in engineering practice, and the above content and application effect in actual system need further research.

Disclosure statement

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