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Improved Dynamic Surface Control for a Class of Nonlinear Systems

Zongcheng Liu, Qiuni Li, Yong Chen, Maolong Lv and Renwei Zuo

***Abstract*— It is well known that backstepping method suffer from the problem of "explosion of terms", which is solved by dynamic surface control (DSC) method. This paper presents an improved dynamic surface control (IDSC) method, which constructs the state errors by directly using virtual control signals, rather than using the signals produced by first-order filters in DSC method. The signals produced by first-order filters will only be used to construct the virtual control laws and actual control law. This modification makes the state errors to be more free from the influence of first-order filters. The stability of systems controlled by the proposed IDSC method is proved based on Lyapunov theorem. Finally, the advantage of IDSC method has been shown by simulation results, and it can be seen in the simulation results that IDSC method has better tracking performance and is more stable than DSC method.**

I. Introduction

As a very powerful control method for nonlinear systems, backstepping method has been attracting more and more attention in control area [1]. Too much remarkable results have been obtained by combining backstepping method with the universal approximations, such as neural networks and logic fuzzy systems [2]-[6]. In these approaches, backstepping method is used as the basic frame of control design, and they can always achieve satisfactory control performances and be robust for disturbances.

While the use of backstepping method becomes wide, a critical drawback of backstepping method was first pointed out and solved in [7]. It was stated in [7] that backstepping method suffers from the problem of unacceptable increasing complexity due to the "explosion of terms", which results from the repeated differentiations of some nonlinear functions in the recursive control design process. Therefore, a low pass filter was firstly introduced [7] in each design step of backstepping method, and the semi-globally boundedness of all the signals in the controlled system is proved. This method is popular known as "DSC" method since dynamic surfaces are introduced by using low pass filters in [7]. Based on the DSC method, too many approximation-based adaptive backstepping approaches have been presented because these approaches are free from the problem of "explosion of terms" from then on. A DSC-based robust adaptive neural control approach has been proposed for strict-feedback nonlinear systems in [8]. However, the bounds of control gain functions are always assumed to be constants while using DSC method. This restrictive condition has been weakened that the control gain functions can be unbounded functions in [9], where a DSC-based adaptive neural control method is designed for a class of non-strict-feedback nonlinear systems. Thus far, the DSC method has already been successfully used for many nonlinear systems by combining the universal approximations [10], [11], [12]. However, it should be noted that the state errors and actual controller for the DSC method are constructed based on the signals produced by passing virtual control signals through first-order filters, which implies the convergence of state errors heavily depends on the first-order filters. This fact will result in the problem that the tracking performance or even the stability of system may degrade rapidly when the time constants of filters are changed.

Motivated by the above discussion, an improved dynamic surface control (IDSC) method is firstly proposed in this paper for a class of nonlinear systems. Though the basic idea of DSC method is utilized, we directly use the original virtual control signals to construct the state errors and actual controller in this paper, which is very different from the standard DSC method. Furthermore, the stability of the closed-loop system controlled by IDSC method has been proved based on Lyapunov theorem. Finally, simulation results are given for the comparison of DSC and IDSC methods to show the advantage of the method in our paper.

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II. Problem Statement

Consider the nonlinear systems investigated in [7] as follows

$$\begin{cases} \dot{x}_i = x_{i+1} + f_i(\bar{x}_i) + \Delta f_i(\bar{x}_i), \quad i = 1, 2..., n-1 \\ \dot{x}_n = u \\ y = x_1 \end{cases} \tag{1}$$

where $\bar{x}_i = [x_1, x_2, ..., x_i]^T \in R^i$ denotes the state vector of the system; $u \in R$ is system control input; $y \in R$ is system output; $f_i(\cdot)$ are unknown continuous functions, $i = 1, ..., n$

We make the same assumptions as [7] as follows

Assumption 1: $|\Delta f_i(\bar{x}_i)| \leq \rho_i(\bar{x}_i)$, where ρ_i is a continuous differentiable function in its arguments. $\Delta f_i(\bar{x}_i)$ is a continuous function.

Assumption 2: f_i is a smooth function in its arguments, and $f_i(0, ..., 0) = 0$.

The control objective is to design a controller such that the system output y tracks the desired trajectory y_d and the resulting tracking error can converge to an arbitrary small neighbourhood of the origin by appropriately choosing design parameters.

Assumption 3: The desired trajectory y_d is sufficiently smooth function of t, and y_d, $\dot{y}_d$ and $\ddot{y}_d$ are bounded, that is, there exists a positive constant B_0 such that $\Omega_0 := \left\{(y_d, \dot{y}_d, \ddot{y}_d) : (y_d)^2 + (\dot{y}_d)^2 + (\ddot{y}_d)^2 \leq B_0\right\}$.

III. Improved Dynamic Surface Control Design

Firstly, we show the standard DSC method for the addressed control problem. From the standard DSC method proposed in [7], we can know that the stable tracking controller for system (1) is shown as follows, for $1 \leq i \leq n-1$

$$S_i = x_i - x_{id} \tag{2}$$

$$\alpha_i = -f_i(\bar{x}_i) - \frac{S_i \rho_i^2}{2\sigma} - K_i S_i + \dot{x}_{id} \tag{3}$$

$$\tau_{i+1}\dot{x}_{i+1d} + x_{i+1d} = -f_i(\bar{x}_i) - \frac{S_i \rho_i^2}{2\sigma} - K_i S_i + \dot{x}_{id} \tag{4}$$

$$S_n = x_n - x_{nd} \tag{5}$$

$$u = \dot{x}_{nd} - K_n S_n \tag{6}$$

where $x_{1d} = y_d$, and σ, K_i and τ_i are design parameters.

From [7], it can be seen that the system stability can be guaranteed and the tracking error are adjustable by the above designed controller under the condition that the initial values of S_i and y_i are within a bounded compact set, where $y_i = x_{id} - \alpha_{i-1}$.

In view of the basic idea of DSC method, the controller proposed by our method, which is so-called 'IDSC', is given as follows

$$e_1 = x_1 - y_d \tag{7}$$

$$e_i = x_i - \alpha_{i-1}, \quad for\ i = 2, ..., n \tag{8}$$

$$\alpha_i = -f_i(\bar{x}_i) - \frac{e_i \rho_i^2}{2\sigma} - K_i e_i + \dot{x}_{id}, \quad for\ i = 1, ..., n-1 \tag{9}$$

$$\tau_{i+1}\dot{x}_{i+1d} + x_{i+1d} = -f_i(\bar{x}_i) - \frac{e_i \rho_i^2}{2\sigma} - K_i e_i + \dot{x}_{id} \quad for\ i = 1, ..., n-1 \tag{10}$$

$$u = \dot{x}_{nd} - K_n e_n \tag{11}$$

Comparing the controllers of DSC method with IDSC method, it can be easily seen the main difference between two methods is that we directly use α_i to construct the state error terms e_i for IDSC method (see (8) and (9)), while x_{i+1d}, produced by passing α_i through a first-order filter, are used to construct the error terms S_i for DSC method (see (2) to (4)).

The reasons why we use α_i to construct the state errors are listed as follows.

1) The purposes of control designs are confining S_i and e_i to zero. However, it should be known that actually the idea values for x_i is α_{i-1}, rather than x_{id}, since there will be no residual terms in the dynamics of e_{i-1}-subsystems. The signals, α_{i-1}, are called the "ideal control input" for the dynamics of e_{i-1}-subsystems with $x_i = \alpha_{i-1}$.

2) . x_{id} is a signal produced by passing α_{i-1} through a first-order filter. Therefore, there must be an error for x_{id} and α_{i-1}. This error is actually unnecessary for the control design, and it is cancelled in IDSC method. This fact makes the IDSC more efficiently to confine the state errors.

3) The error for x_{id} and α_{i-1} may make the controlled system unstable when τ_{i+1} are chosen not small enough. Therefore, we proposed IDSC method.

IV. Stability analysis for IDSC method

As for the IDSC given in this paper, we will give the main result in this section. Define the Lyapunov function as follows

$$V = \sum_{i=1}^{n} V_i + \sum_{i=2}^{n} \frac{y_i^2}{2} \tag{12}$$

$$V_i = \frac{e_i^2}{2}, \quad i = 1, 2, ..., n \tag{13}$$

where $y_i = x_{id} - \alpha_{i-1}$.

We have the following theorem for system (1) with the IDSC method.

Theorem 1: Consider the nonlinear system (1), and the virtual controllers (9), the controller (11) and the first-order filters (10). Given any $p > 0$, if $V(0) < p$, then there exist σ, K_i and τ_i such that all of the signals in the closed-loop system are bounded. Furthermore, the tracking error $e_1 = x_1 - y_d$ converges to a small neighborhood of the origin by appropriately choosing design parameters.

Proof: Firstly, we will analysis the stabilities of e_i, respectively, by consider the time derivative of V_i. Secondly, the stability of the whole closed-control system will be analyzed by using the analysis for each e_i.

Noting (7) and (13), the time derivative of V_1 is

$$\dot{V}_1 = e_1\dot{e}_1 = e_1(\dot{x}_1 - \dot{y}_d) \tag{14}$$

Substituting (1) into (15), and then using (9), we have, for $1 \leq i \leq n-1$

$$\begin{aligned} \dot{V}_1 &= e_1(x_2 + f_1(x_1) + \Delta f_1 - \dot{x}_{1d}) \\ &= e_1(e_2 + \alpha_1 + f_1(x_1) + \Delta f_i - \dot{x}_{1d}) \\ &= e_1\left(e_2 - K_1 e_1 + \Delta f_1 - \tfrac{e_1\rho_1^2}{2\sigma}\right) \\ &\leq e_1 e_2 - K_1 e_1^2 + \tfrac{\sigma}{2} \end{aligned} \tag{15}$$

which implies that the boundedness of e_1 depends on e_2. In the sequel, the boundedness of $e_i, (2 \leq i \leq n-1)$ will be investigated by consider Lyapunov candidate functions V_i.

The time derivative of V_i for $2 \leq i \leq n-1$ is

$$\dot{V}_i = e_i\dot{e}_i = e_i(\dot{x}_i - \dot{\alpha}_{i-1}), \quad 2 \leq i \leq n-1 \tag{16}$$

Noting $y_i = x_{id} - \alpha_{i-1}$, $i = 2, ..., n$, then we have

$$\dot{V}_i = e_i\dot{e}_i = e_i(\dot{x}_i - \dot{x}_{id} + \dot{y}_i), \quad 2 \leq i \leq n-1 \tag{17}$$

In view of (9) and (10), we have

$$\dot{x}_{id} = \frac{1}{\tau_i}\left(\alpha_i - x_{id}\right) = -\frac{y_i}{\tau_i} \tag{18}$$

$$\dot{y}_i = -\frac{y_i}{\tau_i} - \dot{\alpha}_{i-1} \tag{19}$$

By noting (9) and (19), we have, for $i = 1, ..., n-1$

$$\dot{y}_{i+1} = -\frac{y_{i+1}}{\tau_{i+1}} - \sum_{j=1}^{i}\frac{\partial f_j}{\partial x_j}\dot{x}_j - \frac{\dot{e}_i\rho_i^2}{2\sigma} - \frac{e_i\rho_i}{2\sigma}\sum_{j=1}^{i}\frac{\partial \rho_j}{\partial x_j}\dot{x}_j + \frac{\dot{y}_i}{\tau_i} + K_i\dot{e}_i \tag{20}$$

Define

$$\begin{aligned} &B_{i+1}(\bar{e}_{i+1}^T, \bar{y}_{i+1}^T, \bar{K}_i^T, \bar{\tau}_i^T, y_d, \dot{y}_d, \ddot{y}_d) \\ &= -\sum_{j=1}^{i}\tfrac{\partial f_j}{\partial x_j}\dot{x}_j - \tfrac{\dot{e}_i\rho_i^2}{2\sigma} - \tfrac{e_i\rho_i}{2\sigma}\sum_{j=1}^{i}\tfrac{\partial \rho_j}{\partial x_j}\dot{x}_j + \tfrac{\dot{y}_i}{\tau_i} + K_i\dot{e}_i \end{aligned} \tag{21}$$

where $\bar{e}_i = [e_1, ..., e_i]^T$, $\bar{y}_i = [y_2, ..., y_i]^T$, $\bar{K}_i = [K_1, ..., K_i]^T$ and $\bar{\tau}_i = [\tau_2, ..., \tau_i]^T$.

It can be easily known from [7] that the arguments of $B_{i+1}(\cdot)$ are the ones show in (21) and there exist unknown continuous functions $\eta_{i+1},\ i = 1, ..., n-1$ satisfying

$$\begin{aligned} &\left|\dot{y}_{i+1} + \tfrac{y_{i+1}}{\tau_{i+1}}\right| = \left|B_{i+1}(\bar{e}_{i+1}^T, \bar{y}_{i+1}^T, \bar{K}_i, \bar{\tau}_i, y_d, \dot{y}_d, \ddot{y}_d)\right| \\ &\le \eta_{i+1}(\bar{e}_{i+1}^T, \bar{y}_{i+1}^T, \bar{K}_i, \bar{\tau}_i, y_d, \dot{y}_d, \ddot{y}_d) \end{aligned} \tag{22}$$

Substituting (1) and (8) into (17), and then using (9), we have, for $2 \le i \le n-1$

$$\begin{aligned} \dot{V}_i &= e_i\left(x_{i+1} + f_i(\bar{x}_i) + \Delta f_i - \dot{x}_{id} + \dot{y}_i\right) \\ &= e_i\left(e_{i+1} + \alpha_i + f_i(\bar{x}_i) + \Delta f_i - \dot{x}_{id} + \dot{y}_i\right) \\ &= e_i\left(e_{i+1} - K_ie_i + \Delta f_i - \tfrac{e_i\rho_i^2}{2\sigma} + \dot{y}_i\right) \\ &\le e_i\left(e_{i+1} + \dot{y}_i\right) - K_ie_i^2 + \tfrac{\sigma}{2} \end{aligned} \tag{23}$$

And, similarly, we can obtain

$$\begin{aligned} \dot{V}_n &= e_n\left(u - \dot{x}_{nd} + \dot{y}_n\right) \\ &= -K_ne_n^2 + e_n\dot{y}_n \end{aligned} \tag{24}$$

By using (23) and (24), we can know that the time derivative of V defined in (12) satisfies

$$\dot{V} \le \sum_{i=1}^{n-1}e_ie_{i+1} + \sum_{i=2}^{n}e_i\dot{y}_i - \sum_{i=1}^{n}K_ie_i^2 + \frac{(n-1)\sigma}{2} + \sum_{i=2}^{n}y_i\dot{y}_i \tag{25}$$

From the definition of $B_{i+1}(\cdot)$ we have $\dot{y}_{i+1} = -y_{i+1}/\tau_{i+1} + B_{i+1}(\cdot)$. Therefore, (25) can be further rewritten as

$$\begin{aligned} \dot{V} \le &\sum_{i=1}^{n-1}e_ie_{i+1} + \sum_{i=2}^{n}e_i\left(-\frac{y_i}{\tau_i} + B_i(\cdot)\right) - \sum_{i=1}^{n}K_ie_i^2 \\ &+ \frac{(n-1)\sigma}{2} + \sum_{i=2}^{n}\left(-\frac{y_i^2}{\tau_i} + y_iB_i(\cdot)\right) \end{aligned} \tag{26}$$

Noting (22) and using Young's inequality, one obtains

$$e_i\left(-\frac{y_i}{\tau_i} + B_i(\cdot)\right) \le \left(\frac{1}{2\tau_i} + \frac{\eta_i^2(\cdot)}{b}\right)e_i^2 + \frac{1}{2\tau_i}y_i^2 + \frac{b}{4} \tag{27}$$

$$y_iB_i(\cdot) \le \frac{y_i^2\eta_i^2(\cdot)}{b} + \frac{b}{4} \tag{28}$$

$$e_ie_{i+1} \le \frac{e_i^2}{2} + \frac{e_{i+1}^2}{2} \tag{29}$$

where b is any positive constant.

Using (27), (28) and (29), we can rewrite (26) as

$$\begin{aligned} \dot{V} \le &-\left(K_1 - \tfrac{1}{2}\right)e_1^2 - \sum_{i=2}^{n}\left(K_i - 1 - \tfrac{1}{2\tau_i} - \tfrac{\eta_i^2(\cdot)}{b}\right)e_i^2 \\ &- \sum_{i=2}^{n}\left(\tfrac{1}{2\tau_i} - \tfrac{\eta_i^2(\cdot)}{b}\right)y_i^2 + (n-1)\varepsilon \end{aligned} \tag{30}$$

where $\varepsilon = (\sigma + b)/2$.

Consider the sets

$$\Omega_i = \left\{e_1^2 + \cdots + e_i^2 + y_2^2 + \cdots + y_i^2 \le 2p\right\} \tag{31}$$

It is obviously that Ω_i and $\Omega_i \times \Omega_0$ are compact sets. Notice that η_i is a continuous function on $\Omega_i \times \Omega_0$, therefore, η_i has a maximum, say M_i on $\Omega_i \times \Omega_0$. Select $K_1 = 0.5 + a_0$, $K_i = 1 + \frac{1}{2\tau_i} + \frac{M_i^2}{b} + a_1$, where $a_0 > (n-1)\varepsilon/2p$ and $a_1 > (n-1)\varepsilon/2p$. Choose $1/\tau_i = 2\left(M_i^2/b + a_2\right)$, where $a_2 > (n-1)\varepsilon/2p$. Therefore

$$\dot{V} \le -2a_{\min}V + (n-1)\varepsilon - \sum_{i=2}^{n}\left(1 - \frac{\eta_i^2(\cdot)}{M_i^2}\right)\frac{M_i^2}{b}\left(e_i^2 + y_i^2\right) \tag{32}$$

where $a_{\min} = \min\{a_0, a_1, a_2\}$ and $a_{\min} > (n-1)\varepsilon/2p$ It is easily known from (32) that on $V(e_1, ..., e_n, y_2, ..., y_n) = p$, $\eta_i \le M_i$. Therefore, $\dot{V} \le -2a_{\min}V + (n-1)\varepsilon$. Since $a_{\min} > (n-1)\varepsilon/2p$, it follows that $\dot{V} \le 0$ on $V = p$ Therefore, $V \le p$ is an invariant set, namely, if $V(0) \le p$, then $V(t) \le p$ for all $t > 0$ Thus, $e_1, ..., e_n, y_2, ..., y_n$ are bounded, and it is easily to conclude that α_i and u are bounded. Additionally, From (32), it can be seen that

$$\dot{V} \le -2a_{\min}V + (n-1)\varepsilon \tag{33}$$

on $\Omega_i \times \Omega_0$ This implies

$$V(t) \le \left(V(0) - C_1\right)e^{-2a_{\min}t} + C_1 \tag{34}$$

which yields

$$\lim_{t\to+\infty}|e_1| \le \lim_{t\to+\infty}\left|\sqrt{2V(t)}\right| \le \sqrt{2C_1} \tag{35}$$

where $C_1 = (n-1)\varepsilon/2a_{\min}$ Noticing that C_1 can be adjusted to arbitrary small by increasing K_1, K_i and $1/\tau_i$, therefore, the tracking error can be confined to arbitrary small. This completes the proof.

V. SIMULATION RESULTS

In this section, a simulation example is presented to demonstrate the advantages of our method by comparing DSC method. Consider the following nonlinear system:

$$\begin{cases} \dot{x}_1 = 5x_1 + x_2 + x_1\cos(x_1) \\ \dot{x}_2 = u \\ y = x_1 \end{cases} \tag{36}$$

In (36), $f_1(x_1) = 5x_1$, $\Delta f_1(x_1) = x_1\cos(x_1)$, $\rho_1(x_1) = x_1\tanh(x_1) + 0.5$. Therefore, based on the standard DSC method in [7], the tracking controller is proposed as follows

$$
\begin{aligned}
&S_1 = x_1 - y_d \\
&\alpha_1 = -f_1(x_1) - \tfrac{S_1\rho_1^2}{0.2} - 4S_1 + \dot{y}_d \\
&\tau_2 \dot{x}_{2d} + x_{2d} = \alpha_1 \\
&S_2 = x_2 - x_{2d} \\
&u = \dot{x}_{2d} - 4S_2
\end{aligned}
$$

According the IDSC method in our paper and noting Theorem 1, the controller of IDSC is proposed as follows

$$
\begin{aligned}
&e_1 = x_1 - y_d \\
&\alpha_1 = -f_1(x_1) - \tfrac{e_1\rho_1^2}{0.2} - 4S_1 + \dot{y}_d \\
&\tau_2 \dot{x}_{2d} + x_{2d} = \alpha_1 \\
&e_2 = x_2 - \alpha_1 \\
&u = \dot{x}_{2d} - 4e_2
\end{aligned}
$$

The time constants in both methods are $\tau_2 = 0.1$. It can be seen that, for the purpose of comparison, all the design parameters of two method are the same. Moreover, we set the initial conditions of two methods to be the same as well. Specially, let the initial conditions of both methods to be $(x_1(0), x_2(0))^T = (0,0)^T$ and $x_{2d}(0) = 0$ Let $y_d = \sin t$ Then, the simulation results are shown in Figs. 1-3.

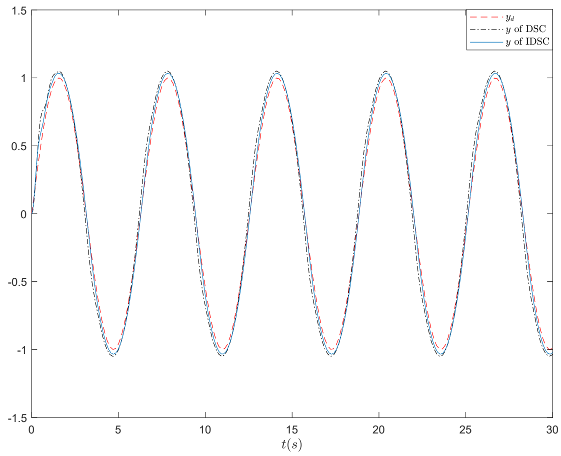

Fig. 1. System output y and desired signal y_d with $\tau_2 = 0.1$

From Fig. 2, we can see that IDSC has smaller tracking error than DSC under the same conditions. From Fig. 1-3, it can be observed that both methods can achieve the control objective, and the IDSC method has better tracking performance than DSC under the same conditions.

To further show the advantage of IDSC method proposed in this paper, we change the design parameter τ_2 to be $\tau_2 = 0.2$, and all the other design parameters and conditions are still the same and not changed. The simulation results for DSC method with $\tau_2 = 0.2$ are reported in Fig. 4-6. From Fig. 4 and 5, it can be seen that system output y is unable to track y_d and the tracking error e_1 is increasing more and more larger under the control of DSC method. For DSC method, system becomes unstable with only τ_2 changed from 0.1 to 0.2.

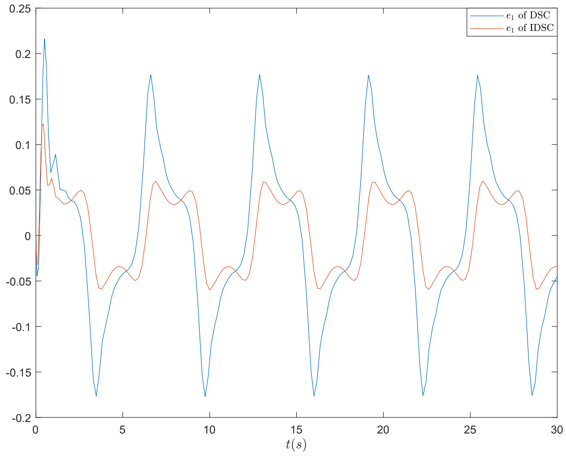

Fig. 2. Tracking errors with $\tau_2 = 0.1$

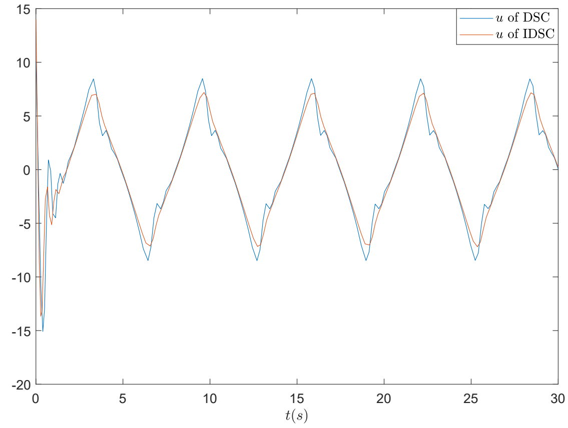

Fig. 3. Control input u with $\tau_2 = 0.1$

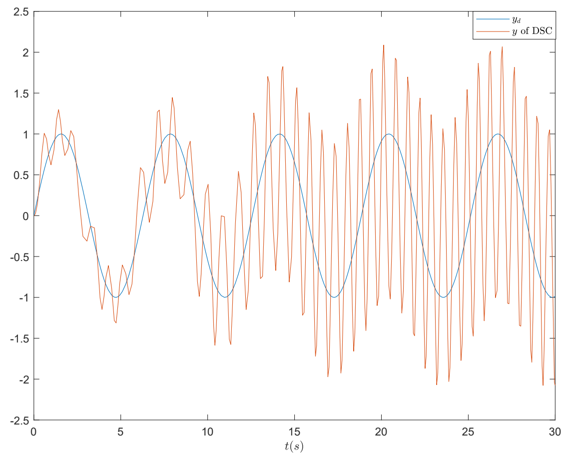

Fig. 4. System output y of DSC and desired signal y_d with $\tau_2 = 0.2$

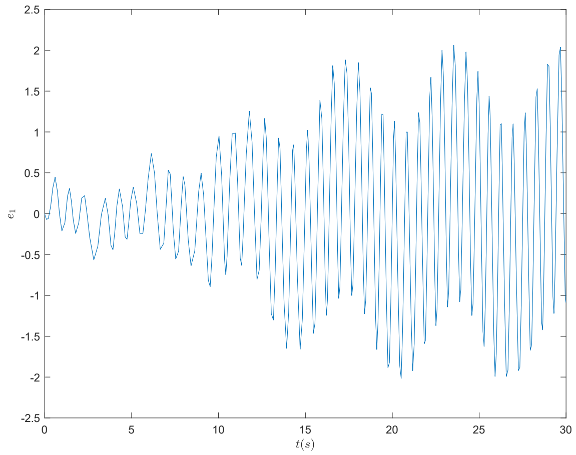

Fig. 5. Tracking error of DSC with τ_2 = 0.2

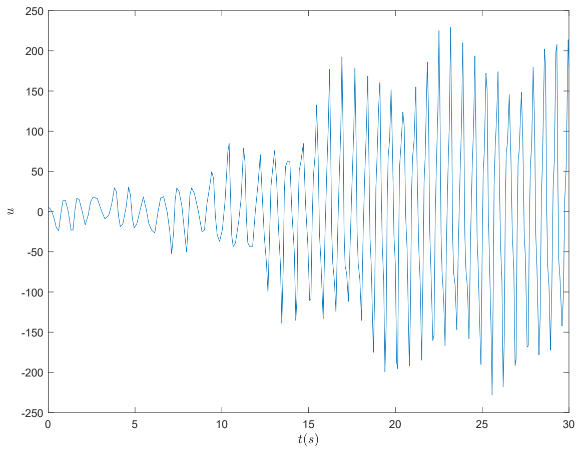

Fig. 6. Control input u of DSC with τ_2 = 0.2

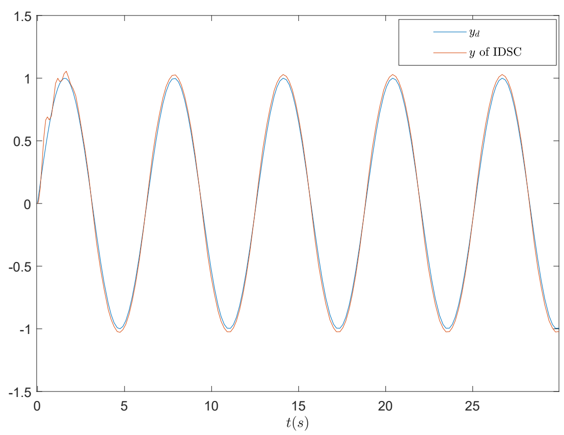

Fig. 7. System output y of IDSC and desired signal y_d with τ_2 = 0.2

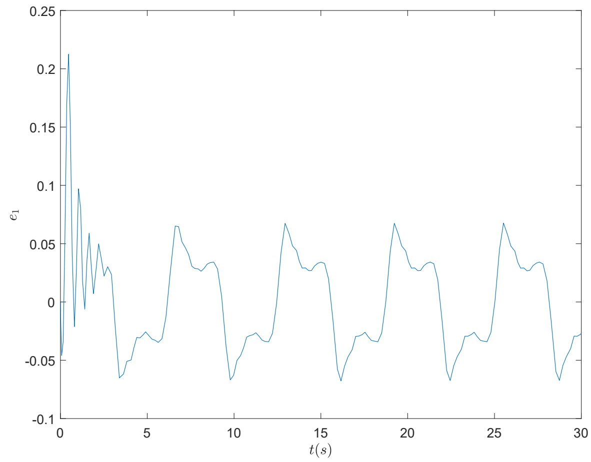

Fig. 8. Tracking error of IDSC with τ_2 = 0.2

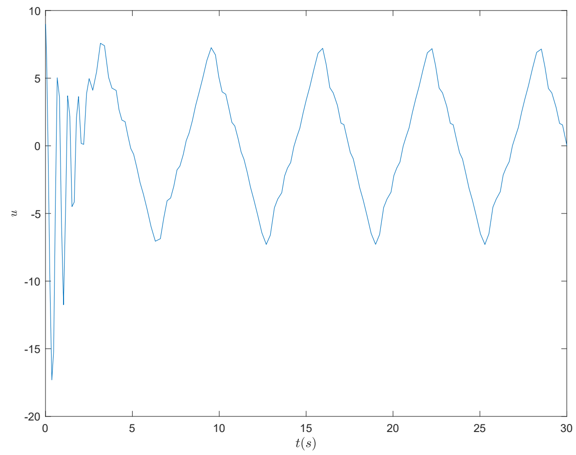

Fig. 9. Control input u of IDSC with τ_2 = 0.2

In the sequel, we use IDSC method for the condition τ_2 = 0.2. All the other design parameters and conditions are not changed. The simulation results for IDSC method with τ_2 = 0.2 are reported in Fig. 7-9. From Fig. 7 and 8, it can be observed that system output y still tracks y_d very well with τ_2 = 0.2, and the tracking error is confined in a satisfactory area as well. It can also be seen that all the signals of system are stable under IDSC method with τ_2 = 0.2.

From these simulation results, we can conclude that under the same conditions, the IDSC method has better tracking performance than the DSC method, and the IDSC-controlled systems are more stable than the DSC-controlled systems when the design parameters changed, such as τ_i changes from 0.1 to 0.2. It should be noted that τ_i is a critical design parameter for the DSC method, since it can always influence the stability of controlled systems. For example, the stability of the controlled systems is always becoming weaker while τ_i are decreasing [7]. Therefore, we propose the IDSC method so as to achieve better tracking performance and enhance the stability of controlled system.

VI. Conclusion

This paper proposes an IDSC method based on the idea of DSC method. By constructing the state errors with the virtual control signals, the proposed method avoids the unnecessary error caused by the introduced first-order filters. The stability of the closed-loop system controlled by IDSC method has been proved based on Lyapunov theorem. Finally, simulation results have been given for the proposed method. From these simulation results, it can be concluded that IDSC method can achieve more stable controlled systems than DSC method, and the tracking performance are fairly good.

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