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ABSTRACT
The aim of this paper is to design a backstepping integral sliding mode controller (BISMC) for speed control of an electromechanical system under uncertainties and disturbances. An integral dynamic is included in traditional sliding surface to improve chattering and steady-state error in tracking a reference signal when parametric uncertainties and disturbances exist. Design and stability of the closed-loop system is realized by Lyapunov criterion in a step by step procedure. Experimental results of the proposed BISMC are compared with those of the traditional sliding mode controller (SMC). The proposed BISMC achieves reasonable tracking performance and exhibits more robust performance concerning parametric uncertainties and disturbances than the traditional SMC.

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Backstepping; non-linear control systems; servosystems; sliding mode control; velocity control

1. Introduction

During the past decades, the design of robust controllers for non-linear dynamical systems with parameter uncertainties and disturbances has attracted enormous research interests [1]. Many design techniques upon the control of non-linear systems have emerged recently such as sliding mode control (SMC), adaptive control (AC) and backstepping control (BSC). Among the most common non-linear feedback control techniques in use today to overwhelm the undesirable effects of uncertainties and disturbances on non-linear systems, the SMC has been used extensively due to their numerous advantages such as robustness to model uncertainties, external disturbance rejection, fast dynamic responses, good transient performance and insensitivity to parameter variations. The sensitivity of non-linear systems under SMC in regard to uncertainties and disturbances is lessened at the price of chattering in several real-world implementations [2]. SMC can deal with uncertainties and disturbances exploiting their lower and upper bounds without parameter adaptation. Contrary to SMC, parametric uncertainties are managed by AC technique with the help of parameter adaptation and their lower and upper bounds need not be used. Thanks to its online adaptation skill, the AC for a non-linear dynamical system with uncertainties in constant or slowly-varying parameters is superior to the SMC. Comparing with SMC methodology to handle parametric or non-parametric uncertainties, the AC methodology can achieve further flexibility to adjust unknown non-linear dynamical systems for the reason that the AC commonly contains an adaptive estimation algorithm that plays an important role in learning. Nevertheless, SMC is superior to AC under uncertainties in rapidly changing parameters and unstructured uncertainties. In addition, SMC handles sudden and large changes in the system dynamics [3].

Various control design methods are based on Lyapunov stability. Stability of the closed-loop control system is simply realized by Lyapunov-based control design. The backstepping approach offers a systematic method for designing a control task to track a desired reference signal by opting for a proper Lyapunov function candidate [4]. The BSC scheme is designed recursively by viewing some of the state variables as virtual controls and devising intermediate control laws. The virtual control law for each step is adopted with the satisfaction of selected Lyapunov functions such that the stability of each subsystem constructed from the overall system can be guaranteed. In order to stabilize the whole closed-loop control system, all destabilizing terms in each first-order subsystem are cancelled [4,5]. Nevertheless, Lyapunov-based BSC is not sufficiently insensitive to parametric uncertainties. Combining the backstepping design and SMC is an alternative scheme to AC for non-linear systems with uncertainties and disturbances. Although this hybrid method is robust to parameter uncertainties and disturbances, it tolerates parametric uncertainties at the price of chattering and tracking error. Integral control action is one of the fundamental mechanisms in feedback control applications. It has an ability to eliminate constant steady-state offset in a closed-loop control system. In practical applications, it gives robustness ability to control systems and helps to solve undesirable problems with unmodelled dynamics, parameter deviations and

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slowly varying disturbances. In order to overcome the drawbacks mentioned above, a backstepping SMC with integral action which is referred to as backstepping integral sliding mode control (BISMC) has been proposed to improve chattering and steady-state error in tracking a reference signal when parametric uncertainties and disturbances occur [1,6–9].

Due to its outstanding speed control characteristics, direct current (DC) motors have been widely used in industrial applications demanding variable speed, changeable load and frequent starting, braking and reversing such as robotics, electric vehicles, numeric control machines and industrial tools [10–12]. Owing to their high-performance motion capability, DC motors are main parts of electromechanical systems as actuator. For electromechanical systems under load variations and parameter uncertainties, speed control via conventional linear proportional-integral-derivative (PID) controllers is not a simple task. Recently, a lot of control methods such as non-linear control, optimal control, variable structure control and AC have been extensively suggested [11,13–15]. In the present research, a non-linear BISMC based on the Lyapunov stability theorem is proposed for an electromechanical system to track the desired reference despite parametric uncertainties and disturbances. The proposed BISMC is devised so that the stability of the entire closed-loop system for the duration of the reaching and sliding periods is guaranteed. Robust stability and tracking error convergence analysis of the BISMC are carried out based on the Lyapunov function candidates. The main focus of the BISMC is to provide improved performance over the traditional SMC in terms of less chattering of the control and smaller steady-state error when the control system is subjected to parametric uncertainties, load variations and disturbances. The proposed BISMC has been experimentally applied to control the speed of an electromechanical system. Experimental results prove that the tracking performance is improved in the presence of uncertainties and disturbances; and at the same time, the stability is maintained. Compared to the traditional SMC [15], the performance of the proposed algorithm is improved in terms of less chattering of the control and smaller steady-state error. The rest of the paper is organized as follows. The experimental set-up and mathematical model of the electromechanical system are briefly introduced in Section 2. Design procedures of the BISMC are presented in Section 3. In Section 4, experimental applications and comparison results of the proposed BISMC and the traditional SMC are reported to show the efficiency of the proposed BISMC. Section 5 draws the final conclusions.

2. Description of the electromechanical system and the experimental set-up

In the current study, the Precision Modular Servo set-up manufactured by Feedback Instruments [16] is regarded to carry out experiments and validate the proposed method. The set-up comprises a brushed dc motor, digital encoder, power supply, pre-amplifier, servo-amplifier, attenuator, input and output potentiometers, gearbox/tachometer and analogue control interface components as shown in Figure 1 [16,17].

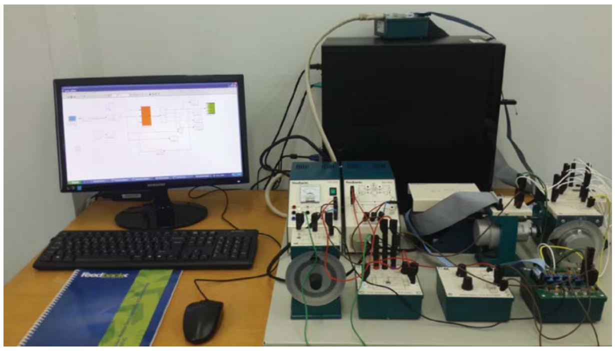

Figure 1. A picture of the experimental set-up.

A comprehensive mathematical model of the electromechanical system is composed of a coupled electrical and a mechanical subsystem. The motor dynamics is described by

$$\begin{aligned}\ddot{\omega}(t) = &-\left(\frac{R}{L}+\frac{\nu}{J}\right)\dot{\omega}(t) - \frac{\nu R + K_t K_b}{LJ}\omega(t)\\ &+\frac{K_g K_t T_{rpm}}{LJ}u(t)\end{aligned} \tag{1}$$

where R and L are the resistance and inductance of the motor, respectively; J is the moment of inertia constant; ν is the viscous friction constant; K_t is the torque constant; $\omega(t)$ is the angular shaft speed; K_b is an electromotive force constant; $u(t)$ is the armature voltage; t is the time; K_g is the gain of the amplifiers; $T_{\mathrm{rpm}} = 60/(2\pi)$ is a constant that converts the motor angular velocity from rad/s to rpm. The DC motor parameters are taken from the manual of Feedback Instruments and presented in Table 1 [16]. The other electromechanical system parameters determined experimentally are $J = 0.0001218\ \mathrm{kgm}^2$ and $\nu = 0.000425\ \mathrm{Nms/rad}$.

Composing the model with dead-zone non-linearity, unmatched uncertainties and disturbances, the electromechanical system can be modelled as a class of non-linear dynamical system by [18–20]

$$\begin{aligned}\ddot{\omega}(t) = &-\left(\frac{R}{L}+\frac{\nu}{J}\right)\dot{\omega}(t) - \frac{\nu R + K_t K_b}{LJ}\omega(t)\\ &+\frac{K_g K_t T_{rpm}}{LJ}u(t) + \xi(\omega,\ \dot{\omega}, t)\end{aligned} \tag{2}$$

Table 1. Values of the electromechanical system parameters [16].

Parameter	Value
K_t	0.052 Nm/A
K_b	0.057 Vs/rad
R	2.5 Ω
L	0.0025 H
K_g	9.6

where $\xi(\omega, \dot{\omega}, t)$ is the total amount of dead-zone non-linearity, unmatched uncertainties and external disturbances. Taking $\eta = [\eta_1, \eta_2]^T = [\omega, \dot{\omega}]^T$ as the state vector, the following general non-linear dynamical equation is obtained:

$$\begin{aligned}\dot{\eta}_1(t) &= \eta_2(t)\\ \dot{\eta}_2(t) &= \theta\phi(\boldsymbol{\eta}, t) + \varphi(\boldsymbol{\eta}, t)u(t) + \xi(\boldsymbol{\eta}, t)\end{aligned} \tag{3}$$

where $\theta\phi(\boldsymbol{\eta}, t)$ is the parametric uncertainties with constant parameter θ, $\phi(\eta, t) = -(\frac{R}{L} + \frac{v}{J})\eta_2 - \frac{vR+K_tK_b}{LJ}\eta_1$, $\varphi(\eta, t) = \frac{K_gK_tT_{\text{rpm}}}{LJ}$ is a constant and has positive sign, $|\xi(x, t)| \leq \xi_{\max}$, and $\xi_{\max}$ is a positive coefficient.

3. Design methods

In this section, after traditional SMC is briefly introduced, the proposed BISMC shall be presented. The SMC based on discontinuous control laws is an efficient and robust tool to control non-linear dynamical systems with uncertainties [21,22]. The control law for SMC comprises both an equivalent control $u_{\text{eq}}(t)$ and a discontinuous control $u_d(t)$ [22,23]:

$$u(t) = u_d(t) + u_{\text{eq}}(t) \tag{4}$$

In order to design an SMC for the electromechanical system in (3), first a sliding surface is chosen as follows:

$$\sigma(t) = k_1e(t) + \dot{e}(t) \tag{5}$$

using the tracking error

$$e(t) = y(t) - y_d(t) = \eta_1(t) - y_d(t) \tag{6}$$

where $k_1 > 0$ and the output is $y(t) = \omega(t) = \eta_1(t)$.

Afterwards, let us design the equivalent control by setting the time derivative of the sliding surface to zero

$$u_{\text{eq}}(t) = \frac{1}{\varphi(\eta, t)}[-k_1\dot{e}(t) - \theta\phi(\eta, t) + \ddot{y}_d(t)] \tag{7}$$

Consider a Lyapunov function candidate to design a discontinuous control $u_d(t)$

$$V(\sigma) = \frac{1}{2}\sigma^2(t) \geq 0 \tag{8}$$

The derivative of $V(\sigma(t))$ along the trajectories of the dynamic system in (3) and the sliding surface in (5) is

$$\begin{aligned}\dot{V}(\sigma(t)) &= \sigma(t)\dot{\sigma}(t)\\ &= \sigma(t)[k_1\dot{e}(t) + \theta\phi(\eta, t) + \varphi(\eta, t)(u_{\text{eq}}(t)\\ &\quad + u_d(t)) + \xi(\eta, t) - \ddot{y}_d(t)]\end{aligned} \tag{9}$$

Substituting (7) into (9), one has

$$\begin{aligned}\dot{V}(\sigma(t)) &= \sigma(t)[\varphi(\eta, t)u_d(t) + \xi(\eta, t)]\\ &\leq -K\sigma(t)\text{sign}(\sigma(t))\\ &= -K|\sigma(t)| \leq 0\end{aligned} \tag{10}$$

with the discontinuous control law

$$u_d(t) = -\frac{1}{\varphi(\eta, t)}K\text{sign}(\sigma(t)) \tag{11}$$

where

$$K \geq \xi_{\max} \geq |\xi(x, t)|, \textit{ and } \text{sign}(\sigma) = \begin{cases} 1, & \sigma(t) > 0\\ 0, & \sigma(t) = 0\\ -1, & \sigma(t) < 0\end{cases}$$

Consequently, the closed-loop dynamic system trajectory reaches the sliding surface in finite time and remains therein due to the fact that $\dot{V}(\sigma(t)) = -K|\sigma(t)| \leq 0$.

One of the disadvantageous characteristics of SMC is the chattering originating from imperfections in switching devices. One of the numerous approaches to diminish chattering is to utilize a saturation function instead of the signum function. Therefore, one can use the following discontinuous control instead of (11):

$$u_d(t) = -\frac{1}{\varphi(\eta, t)}K\text{sat}(\sigma(t)/\Delta) \tag{12}$$

where $\text{sat}(\Xi) = \begin{cases} \Xi, & |\Xi| \leq 1\\ \text{sign}(\Xi), & |\Xi| > 1\end{cases}$

In order to overcome some drawbacks of the traditional SMC designed above such as chattering and steady-state error or tracking error due to uncertainties and disturbances, the BISMC is proposed. Step by step design procedures are given in what follows and the block diagram of the proposed BISMC is portrayed in Figure 2. Considering again the electromechanical system given in (3) and the tracking error in (6), one gets its time derivative in the first step as follows [24–26]:

$$\dot{e}(t) = \dot{\eta}_1(t) - \dot{y}_d(t) \tag{13}$$

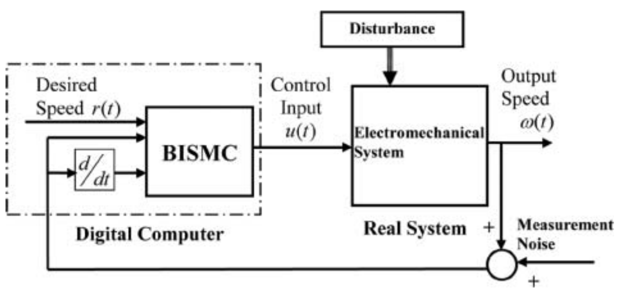

Figure 2. Block diagram of the BISMC.

Choosing an appropriate Lyapunov function helps to ensure the stability of the non-linear system in the first step as follows:

$$V_0(e) = \frac{1}{2}e^2(t) > 0, \ \forall e \neq 0 \tag{14}$$

Time derivative of the above equation is

$$\dot{V}_0(e(t)) = e(t)\dot{e}(t) = e(t)[\eta_2(t) - \dot{y}_d(t)] \tag{15}$$

If the state $\eta_2(t)$ in (3) is viewed as a virtual input $\eta_2(t) = \delta_0(e) = -c_1 e(t) + \dot{y}_d(t)$, the origin of $\dot{e}(t) = -c_1 e(t)$ is globally asymptotically stable because $\dot{V}_0(e) = -c_1 e^2(t) < 0, \ \forall (e \neq 0) \in \mathcal{R}$ for $c_1 > 0$.

To design a feedback control law by adding an integral action which contributes to the control bandwidth and tracking precision for parametric uncertainty and robustness to high frequency unmodelled dynamics, the virtual control becomes

$$\eta_2(t) = \delta(e) = -c_1 e(t) - c_2 \int_0^t e(\tau)d\tau + \dot{y}_d(t) \tag{16}$$

where $c_2 > 0$. Substituting (16) into (13), one has

$$\dot{e}(t) = -c_1 e(t) - c_2 \int_0^t e(\tau)d\tau \tag{17}$$

Modifying the Lyapunov function in (14) with the integral action, one obtains

$$V_1(e) = \frac{1}{2}e^2(t) + \frac{1}{2}c_2 \left(\int_0^t e(\tau)d\tau \right)^2 > 0, \ \forall e \neq 0 \tag{18}$$

The derivative of the above equation with respect to time is

$$\dot{V}_1(e) = e(t)\dot{e}(t) + c_2 e(t) \int_0^t e(\tau)d\tau \tag{19}$$

Substitution of (17) into (19) results in

$$\dot{V}_1(e) = -c_1 e^2(t) \leq 0 \tag{20}$$

This means that the system augmented by an integral action is asymptotically stable in the first step. In order to backstep, if the change of variables is applied to

$$\sigma(t) = \eta_2(t) - \delta(e) = \eta_2(t) + c_1 e(t) + c_2 \int_0^t e(\tau)d\tau - \dot{y}_d(t) \tag{21}$$

the system under control can be transformed into the following form:

$$\dot{e}(t) = \sigma(t) - c_1 e(t) - c_2 \int_0^t e(\tau)d\tau \tag{22}$$

In order to combine backstepping design and SMC, let us determine the sliding surface using (22)

$$\sigma(t) = \dot{e}(t) + c_1 e(t) + c_2 \int_0^t e(\tau)d\tau \tag{23}$$

Initial conditions $\dot{e}(0)$ and $e(0)$ can be included in the sliding surface in (23) in order to define the integral to within a constant. This constant may be selected to set $\sigma(t=0)$ to zero regardless of the initial condition of the desired trajectory. For the sake of simplicity, the initial conditions are set to zero; that is, $\dot{e}(0) = 0$ and $e(0) = 0$. A necessary and sufficient condition for the tracking error to stay on the sliding surface is $\dot{\sigma}(t) = 0$

$$\dot{\sigma}(t) = \ddot{e}(t) + c_1 \dot{e}(t) + c_2 e(t) = 0 \tag{24}$$

In order to ensure the stability of the proposed BISMC, the following composite Lyapunov function is assumed to be

$$V_c(e) = V_1(e) + \frac{1}{2}\sigma^2(t) > 0, \ \forall e \neq 0 \tag{25}$$

The derivative of the Lyapunov function in (25) along the solutions of (22) and the derivative of (21) is

$$\begin{aligned}
\dot{V}_c(e) &= e(t)\left[\sigma(t) - c_1 e(t) - c_2 \int_0^t e(\tau)d\tau\right] \\
&\quad + c_2 e(t) \int_0^t e(\tau)d\tau + \sigma(t)[c_1 \dot{e}(t) + c_2 e(t) \\
&\quad + \theta\phi(\boldsymbol{\eta}, t) + \varphi(\boldsymbol{\eta}, t)u(t) + \xi(\boldsymbol{\eta}, t) - \ddot{y}_d] \\
&= -c_1 e^2(t) + \sigma(t)e(t) + \sigma(t)[c_1 \dot{e}(t) + c_2 e(t) \\
&\quad + \theta\phi(\boldsymbol{\eta}, t) + \varphi(\boldsymbol{\eta}, t)u(t) + \xi(\boldsymbol{\eta}, t) - \ddot{y}_d] \\
&= -c_1 e^2(t) + \sigma(t)[c_1 \dot{e}(t) + (1 + c_2)e(t) \\
&\quad + \theta\phi(\boldsymbol{\eta}, t) + \varphi(\boldsymbol{\eta}, t)u(t) + \xi(\boldsymbol{\eta}, t) - \ddot{y}_d]
\end{aligned} \tag{26}$$

To make $\dot{V}_c(e)$ negative definite, the bracketed term multiplying $\sigma(t)$ is set to $-c_3\sigma(t)$ for $c_3 > 0$. Therefore, the time derivative of the Lyapunov function becomes negative definite

$$\dot{V}_c(e) = -c_1 e^2(t) - c_3 \sigma^2(t) \tag{27}$$

To design the feedback control law in order that the stability of the whole system is guaranteed, let us select the discontinuous control

$$u_d = -\frac{1}{\varphi(\boldsymbol{\eta}, t)}\Gamma \mathrm{sign}(\sigma(t)) \tag{28}$$

and the equivalent control

$$u_{\mathrm{eq}}(t) = \frac{1}{\varphi(\boldsymbol{\eta}, t)}[-c_1\dot{e}(t) - (1+c_2)e(t) - c_3\sigma(t) - \theta\phi(\boldsymbol{\eta}, t) + \ddot{y}_d] \tag{29}$$

With help of the control laws in (28) and (29), the stability proof of the electromechanical system controlled by the proposed BISMC can be made as follows:

$$\dot{V}_c(e) = -c_1e^2(t) - c_3\sigma^2(t) + \sigma(t)\xi(\boldsymbol{\eta}, t) - \Gamma\,|\,\sigma(t)\,| < 0, \quad \forall(e \neq 0, \sigma \neq 0) \in \mathcal{R} \tag{30}$$

From the above analysis, it is obvious that the reaching condition is guaranteed for $\Gamma \geq \xi_{\max} \geq |\,\xi(\eta, t)\,|$. Since $V_c(e)$ in (25) is radially unbounded, the origin of the closed-loop system is globally asymptotically stable. Furthermore, the control law makes the output of the system in (2) asymptotically track the desired trajectory. It means that tracking error approaches zero as time goes to infinity. Putting (28) and (29) together and including (23), the feedback control law can be rewritten as follows:

$$u(t) = \frac{1}{\varphi(\boldsymbol{\eta}, t)}\Big[-(c_1+c_3)\dot{e}(t) - (1+c_2+c_1c_3)e(t) - c_2c_3\int_0^t e(\tau)d\tau - \theta\phi(\boldsymbol{\eta}, t) + \ddot{y}_d - \Gamma\mathrm{sign}(\sigma(t))\Big] \tag{31}$$

4. Experimental applications and results

In order to confirm the effectiveness of the proposed BISMC, it is applied to the real electromechanical system mentioned in Section 2. In order to avoid high frequency measurement noise, a low-pass filter with the transfer function of $G_f(s) = 100/(s+100)$ is used. The saturation function in (12) instead of the signum function is employed for the discontinuous control $u_d(t)$ because of its chattering-decreasing attributes. For all experiments, the values of the controller parameters $c_1 = k_1 = 600$, $c_3 = 10$ and the zero initial state conditions $\eta(0) = [\eta_1, \eta_2]^T = [\omega, \dot{\omega}]^T = [0, 0]^T$ of the electromechanical system are used. A step reference trajectory of 2100 rpm in magnitude is applied to the control system for all experiments.

In the first experiment, the nominal model with the matched uncertainty $\theta = 1$ for the electromechanical system is supposed. The controller parameters $\Delta = 2 \times 10^5$ and $K = \Gamma = 3 \times 10^6$ are chosen for both the proposed BISMC and the traditional SMC [15]. The coefficient of the integral action for the proposed BISMC is set to zero ($c_2 = 0$) since no parametric uncertainty is presumed. The speed responses and the corresponding control inputs of the proposed BISMC and the traditional SMC to a step reference of 2100 rpm are depicted in Figure 3(a,b). The performance of the proposed BISMC according to rise time and settling time is much better than that of the traditional SMC. The rise time and settling time for the traditional SMC may be shortened by fine-tuning the parameter k_1 but in that case, overshoot would increase. Roughly, the selection of the parameter k_1 is an optimum trade-off between the speed of the response and overshoot. The proposed BISMC and SMC show almost same steady-state error of about 15 rpm. As seen in Figure 3(a), the BISMC is two times faster than the other in response. The settling time for the BISMC is approximately 0.25 s but that for the SMC is about 0.5 s. Almost no overshoot is observed for both controllers. Input signals of the controllers converge with different speeds as shown in Figure 3 (b). The BISMC has a much faster and a little larger control signal than the other within 0.4 s. In addition, the BISMC input increases to a higher level than the

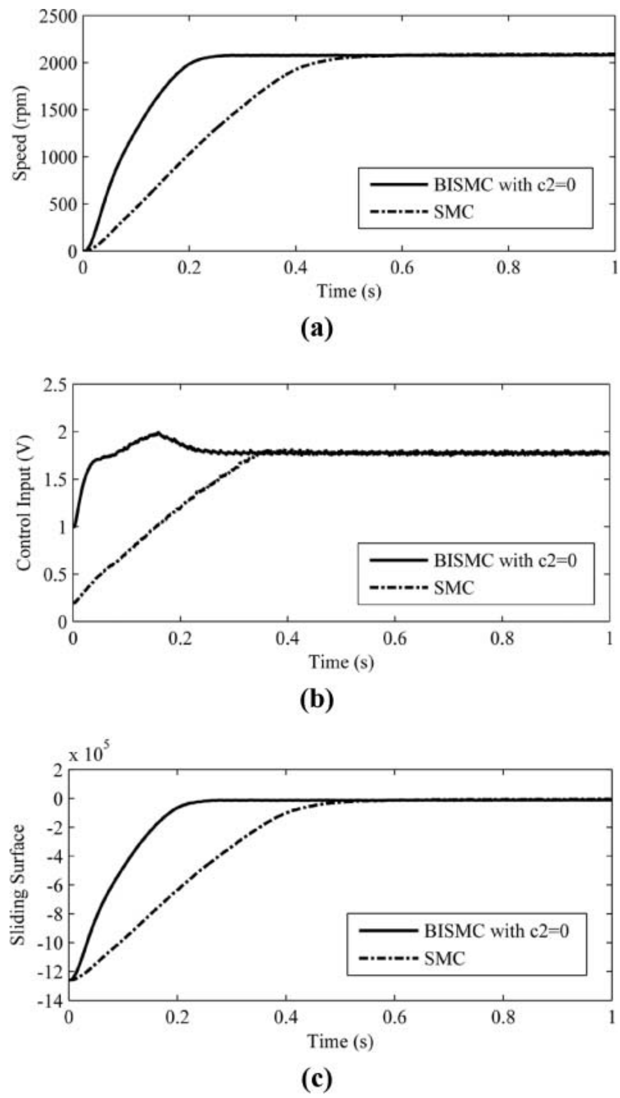

Figure 3. Experimental results for nominal model with the matched uncertainty $\theta = 1$: (a) Speed, (b) Control input, (c) Sliding surface.

other in the transient phase. This is the reason why the proposed control system has a faster response. The faster and larger control that enables the electromechanical system output to reach the set-point rapidly but not to cause overshoot or oscillation is generated by the backstepping part of the BISMC. Both the sliding surfaces for both the controllers are smooth as can be seen in Figure 3(c). They converge to zero since the controllers are designed based upon the nominal model and there does not exist parametric uncertainty. No chattering is observed on both the surfaces.

The last experiment is carried out for the arguments upon the behaviours of both the controllers for the electromechanical system under the matched uncertainty $\theta = 0.8$. The objective of the experiment is to compare the performance of the proposed BISMC with that of the traditional SMC for robustness to parameter uncertainty. The coefficient of the integral action for the proposed BISMC is adjusted as $c_2 = 12,000$ so that the output of the electromechanical system under parametric uncertainty can closely track the desired reference signal. The experiment is repeated for the proposed BISMC with the integral coefficient $c_2 = 0$ to validate the importance of the integral action. The controller parameters $\Delta = 2 \times 10^5$ and $\Gamma = 3 \times 10^6$ are chosen for the proposed BISMC with $c_2 = 12,000$. Those parameters are selected as $\Delta = 2 \times 10^4$ and $K = 1 \times 10^7$ for the BISMC with $c_2 = 0$ and the traditional SMC. The speed responses, the corresponding control inputs and the sliding surfaces of the proposed BISMC with and without integral action and the traditional SMC to a step reference of 2100 rpm are illustrated in Figure 4. The shorter rise and settling times and smaller steady-state error are achieved from the proposed BISMC with $c_2 = 12,000$ as compared with the SMC and the BISMC with $c_2 = 0$ as seen in Figure 4(a). The proposed BISMC with $c_2 = 12,000$ does not display overshoot whereas the SMC and the BISMC with $c_2 = 0$ exhibit undesirable amount of overshoot. Settling times for the proposed BISMC with $c_2 = 12,000$, the BISMC with $c_2 = 0$ and the SMC are about 0.25, 0.28 and 0.33 s, respectively. The steady-state errors for the proposed BISMC with $c_2 = 12,000$, the BISMC with $c_2 = 0$ and the SMC are 15, 22 and 25 rpm, respectively. It is obvious that the proposed BISMC has less output variation from the trajectory in steady-state compared to the SMC. This makes certain that the proposed BISMC is more robust than the SMC for the system under parametric uncertainties. It is seen from Figure 4(b) that the BISMC control law struggles to track the desired trajectory more closely than that of the SMC when the control system is subjected to any parametric uncertainty. As can be observed from the figure, the undesirable high frequency chattering that is supposed to be available in the control input signal is significantly reduced by the proposed BISMC with $c_2 = 12,000$ as a consequence of chattering-lessening characteristic of the integral action included in the control law of the proposed controller. The proposed BISMC achieves not only satisfactory tracking control but also chattering-free control. The sliding surfaces produced by the BISMC with $c_2 = 0$ and the SMC converge to zero whereas the proposed BISMC with $c_2 = 12,000$ does converge to any constant value instead of zero since the integral action brings the output of the control system very close to the desired reference signal without chattering despite parametric uncertainty. However, the time derivative of the sliding surface converges to zero. This allows the tracking error to converge close to zero as well.

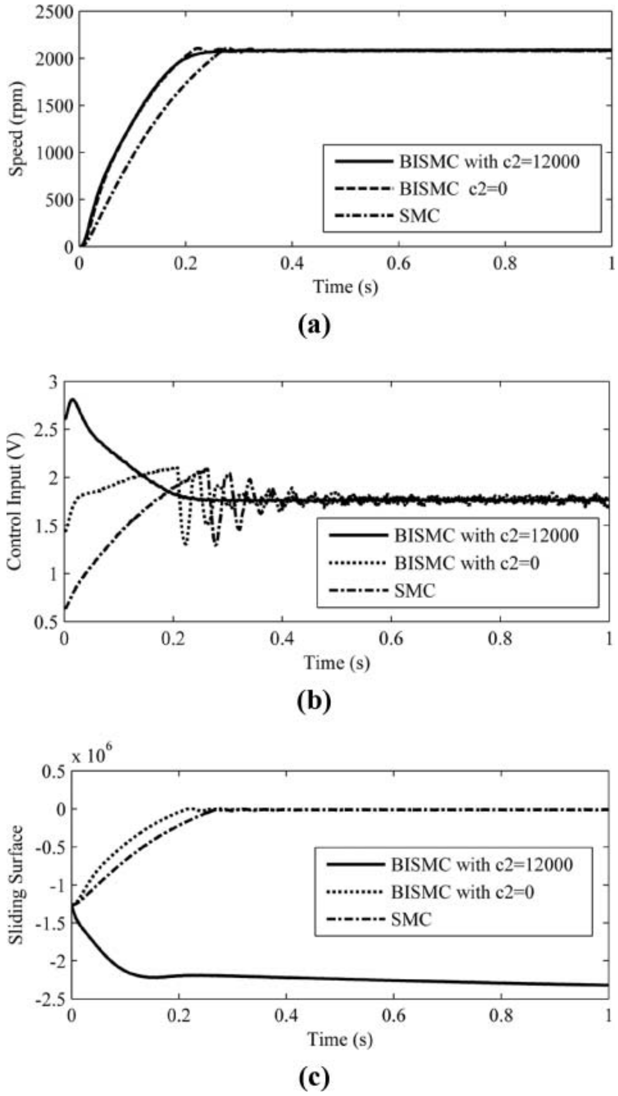

Figure 4. Experimental results for nominal model with the matched uncertainty $\theta = 0.8$: (a) Speed, (b) Control input, (c) Sliding surface.

5. Conclusion

In this study, the BISMC for an electromechanical system is suggested in order to overcome the difficulties in parametric uncertainty. Comparisons with a traditional SMC for speed control are introduced. In addition, stability analysis of the control system based on Lyapunov method is presented. In order to confirm the effectiveness of the proposed controller, it is implemented on a real electromechanical system. Along with the results of the experiments, the proposed BISMC makes an improvement in steady-state error, decreases chattering and compensates parameter variations compared to the traditional SMC. The proposed BISMC provides not only a faster transient response but also a smaller steady-state error provided that the integral coefficient of the controller is adequately tuned. Also, the proposed BISMC decreases chattering on the control signal and at the same time, it improves robustness against parametric uncertainty.

Disclosure statement

No potential conflict of interest was reported by the author.

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