Improved Third Order PID Sliding Mode Controller for Electrohydraulic Actuator Tracking Control

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Abstract—An electrohydraulic actuator (EHA) system is a combination of hydraulic systems and electrical systems which can produce a rapid response, high power-to-weight ratio, and large stiffness. Nevertheless, the EHA system has nonlinear behaviors and modeling uncertainties such as frictions, internal and external leakages, and parametric uncertainties, which lead to significant challenges in controller design for trajectory tracking. Therefore, this paper presents the design of an intelligent adaptive sliding mode proportional integral and derivative (SMCPID) controller, which is the main contribution toward the development of effective control on a third-order model of a double-acting EHA system for trajectory tracking, which significantly reduces chattering under noise disturbance. The sliding mode controller (SMC) is created by utilizing the exponential rule and the Lyapunov theorem to ensure closed-loop stability. The chattering in the SMC controller has been significantly decreased by substituting the modified *sigmoid* function for the signum function. Particle swarm optimization (PSO) was used to lower the total of absolute errors to adjust the controller. In order to demonstrate the efficacy of the SMCPID controller, the results for trajectory tracking and noise disturbance rejection were compared to those obtained using the proportional integral and derivative (PID), the proportional and derivative (PD), and the sliding mode proportional and derivative (SMCPD) controllers, respectively. In conclusion, the results of the extensive research given have indicated that the SMCPID controller outperforms the PD, PID, and SMCPD controllers in terms of overall performance.

Keywords—Sliding Mode Control (SMC); Electrohydraulic Actuator (EHA); PID Sliding Mode Controller; Particle Swarm Optimization (PSO)

I. INTRODUCTION

Electrohydraulic actuator (EHA) systems are very practical and dependable because of their small size in relation to their power, high force-generating capabilities, and quick reaction times [1], [2]. These characteristics make them popular in construction equipment, which is also known as mobile hydraulic machines [3], for which they are employed often. While known to be a nonlinear system with significant uncertainties (due to the presence of friction, leakage, and fluctuating oil temperature), the high-frequency behavior of the servo valve, and external disturbances, the EHA system is also known to be a nonlinear system with significant uncertainties [4]-[15].

Furthermore, because of the nonlinear relationship between pressure and flow rate [16]-[22], it is difficult to operate the EHA system such that it functions effectively. When the EHA system is subjected to substantial external disturbances, researchers in [23] point out that greater attention should be devoted to the control issue, which they believe is warranted. Accordingly, PD or PID controller is extensively used in industrial control systems due to its design simplicity and ease of implementation. It is commonly used in EHA control applications to compare the tracking performance with different control systems [24]-[29]. Furthermore, in order to ensure optimum performance in position tracking, the PD and PID controllers implementation required extensive work on identifying the optimal value of the controller parameters [30]. Consequently, a PID controller with a Ziegler-Nichols approach to get the best parameter values was proposed in [31]. The proposed controller is tested in real-time tests and simulation with a linear discrete EHA model obtained by a system identification technique with a best fit of 92.8%. The outcome demonstrated a considerable improvement in position tracking performance. However, the comparison between the real-time tests and simulation outcome showed a considerable divergence due to the neglect of nonlinearity and uncertainties characteristic while obtaining the linear model.

Nonlinear systems should not be controlled by a PD or PID controller since the controller is linear [32], [33]. Because of this, researchers have looked for alternatives, such as adaptive control systems [34]. As an alternative to traditional control tactics, a nonlinear control strategy based on variable order models, known as sliding mode control (SMC), has been successfully applied to the regulation of nonlinear and uncertain systems during the last five decades [35]. It was frequently used in the control of nonlinear complex systems, such as the EHA system, and was very effective. In nonlinear systems, the SMC is a conventional nonlinear control approach with a high gain and resilience that was created to cope with nonlinear and unpredictable

systems. It does, however, create high-frequency oscillations in the controller's output, which is undesirable. Chattering is a term that refers to fast oscillations that are potentially hazardous to the final control element in a control system [36]-[53].

In this work, two types of controllers are principally addressed: the PD and the PID. Using a sliding mode PD (SMCPD) controller and a sliding mode PID (SMCPID) controller, the task is carried out in the following steps. The robustness qualities of sliding mode control have made it a popular approach for robust control of uncertain systems, owing to its efficiency in dealing with uncertainties and its low cost. A sliding mode controller, in theory, can deal with a wide range of uncertainties as well as limited external disturbances since it is only constrained by practical limits on the amplitude of the control signals it generates. While the SMC ensures that the final control system will be stable and durable, it does so at the expense of chattering effects, which may be deliberately generated. Unfortunately, even a perfect sliding mode controller will have a discontinuous switching function [38] because of the way it is designed. In actuality, unpleasant chattering will occur as a result of the inaccuracy of the switching process. Instead of the discontinuous signum function used in standard sliding mode control, a sigmoid function is employed to replace it during the reaching phase.

The purpose of this research is to present a sliding mode PID controller, and a third-order model of a double-acting EHA system is used as a nonlinear system case study to accomplish this goal. The SMC control has been improved with the addition of a PID sliding surface to increase the performance of the EHA system's trajectory tracking. The Lyapunov criteria are used to demonstrate the stability of the proposed control strategy. Simulating and comparing the performance of the proposed control methodology to PD, PID, and SMCPD controllers have shown the utility of the proposed control methodology. The following is a breakdown of the contributions made by the paper:

a) The SMCPID controller is presented and successfully demonstrated for effective control on a third-order model of a double-acting EHA system for trajectory tracking under noise disturbance.
b) Chattering was significantly reduced when the suggested controller's optimized settings were adjusted. This was accomplished by employing the PSO technique to acquire the optimized parameters.
c) A comparison of the SMCPID controller with the PD, PID, and SMCPD controllers revealed that the SMCPID controller outperformed the others.

Furthermore, this paper is structured as follows: Section II presents the dynamical model of a double-acting EHA system. Section III explains how the suggested sliding mode control was developed. Section IV presents the simulation findings for the performance of a double-acting electrohydraulic actuator system. Section V focuses on the performance and potential expansion of the planned control.

II. THE DYNAMICAL MODEL OF A DOUBLE-ACTING EHA SYSTEM

The EHA system may be modeled using one of two methodologies available at the moment. The first method is mathematical modeling, in which modeling is performed by the use of mathematical equations, which, of course, make an effort to accurately describe the whole system as accurately as possible. Setting up or recognizing the appropriate model, on the other hand, is difficult because such a system is naturally characterized by a wide range of uncertainties, notable nonlinearities, and time-varying characteristics, making conventional modeling a difficult and time-consuming process to complete. In this example, things like the bulk modulus of the oil, the temperature at which it was used, and the pressure-flow characteristics of it all play a role in the uncertainty in the parametric uncertainty [54].

The second method is system identification, which entails modeling the system using sets of input and output data, either with or without previous knowledge of the system's operation. According to one definition, system identification is the process of finding the mathematical model from sets of input and output data, with the error representing the disparity between the mathematical model and the actual system. In engineering, system identification is quickly becoming one of the most important areas to study and work on [22].

Moreover, the model structure estimation is constructed using a mathematical derivation based on the EHA system shown in Fig. 1 and by neglecting non-linearities such as internal or external leakage and valve dynamics, the symbols for which are displayed in Table I [55]. Eq. (1) denotes the equation that describes the relationship between the input signal, the servo valve gain, and the spool valve position, and Eq. (2) denotes the equation that describes the relationship between the overall oil flow dynamics of the EHA system derived from a Taylor series linearization. As a side note, Eq. (3) can be used to show how much the load pressure changes over time.

$$x_v = K_v u \tag{1}$$

$$Q_L = K_q x_v - K_c P_L \tag{2}$$

$$\dot{P}_L = \frac{4\beta_e}{V_t}(Q_L - C_{tp}P_L - A_p\dot{y}) \tag{3}$$

As a result, the force produced by the actuator from a total mass coupled to the piston's end is represented as

$$F_a = A_p P_L = M_t \ddot{y} \tag{4}$$

Substituting Eqs. (2) and (3) into the derivative of Eq. (4) produces

$$M_t \dddot{y} + M_t \ddot{y} \frac{4\beta_e}{V_t}(K_c + C_{tp}) + A_p{}^2 \frac{4\beta_e}{V_t}\dot{y}$$
$$= A_p \frac{4\beta_e}{V_t} K_q K_v u \tag{5}$$

Let $a_1 = A_p \frac{4\beta_e}{M_t V_t} K_q K_v$, $a_2 = \frac{4\beta_e}{V_t}(K_c + C_{tp})$ and $a_3 = A_p{}^2 \frac{4\beta_e}{M_t V_t}$ the Eqn. (5) becomes,

$$\dddot{y} = u a_1 - a_2 \ddot{y} - a_3 \dot{y} \qquad (6)$$

Taking a Laplace transform on Eq. (6) becomes,

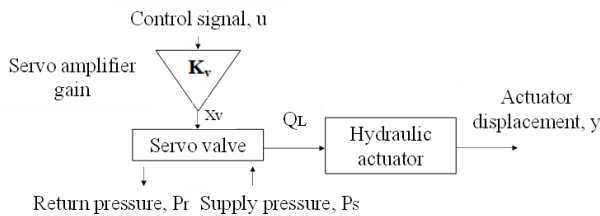$$\frac{Y(s)}{U(s)} = \frac{a_1}{s(s^2 + a_2 s + a_3)} \qquad (7)$$

Fig. 1.   The EHA system for model structure estimation

TABLE I.   Symbol representation of EHA system for estimation

Symbol	Representation
u	Input signal
x_v	Spool valve position
K_v	Servo valve gain
Q_L	Total oil flow
K_q	Flow-gain coefficient
P_L	Load pressure
K_c	Flow-pressure coefficient
β_e	Effective bulk modulus
V_t	Total oil volume
C_{tp}	Total leakage coefficient
A_p	Surface area of the piston
y	Piston position
F_a	Actuator force
M_t	Total mass

As a result, utilizing system identification methods, the dynamical model of the double-acting EHA system with 80 bar supply pressure is developed. The time-domain input-output data collected by the experimental hardware and software arrangement presented in Fig. 2 is utilized to determine the continuous transfer function. The arrangement has a computer unit installed with MATLAB and SIMULINK software; a data acquisition system (DAQ) system with a power supply unit, and a hydraulic plant consisting of a hydraulic power pack, a proportional valve (Bosch Rexroth 4WREE 6 E08-2X/G24K31/A1V), and a hydraulic actuator (Bosch Rexroth – 200 mm single-rod double acting cylinder) attached with a wire displacement sensor.

Furthermore, the MATLAB/System identification toolbox is utilized to get a transfer function parameter based on Eq. (7) that matches the detailed model by examining the collection of input and output data.
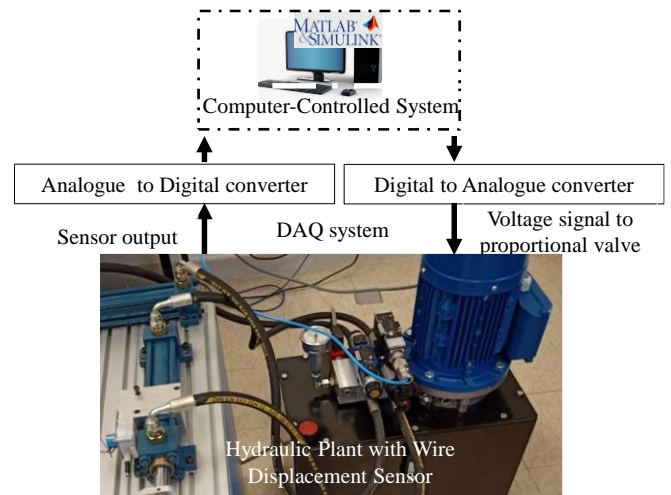

Fig. 2.   Experimental hardware and software arrangement

III.   Design of controllers

It is described in this section how to develop controllers for the PD, PID, SMCPD, and SMCPID signal processing systems. The fundamental aim of the control method is to provide high end-effector tracking performance while also maintaining stability in the system. An SMC is a model-based control system in which the output of the controller is built differently for each system under the controller's control. According to the Lyapunov stability theory, the design method ensures that the system will remain stable under any conditions. It is a kind of resilient controller that allows for the handling of uncertainty in plant models while still preserving performance and reliability.

A.   PD and PID controllers design

In this section, PD and PID control structures are presented. The error signal, $e(t)$ depicted in Fig. 3, is employed to cause the proportional, integral, and derivative activities.
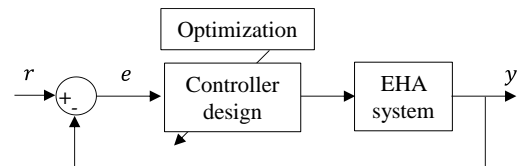

Fig. 3.   The block diagram of the controller design

Then, the formed control signal of PD $(u(t)_{PD})$ and PID $(u(t)_{PID})$ is employed in the EHA system, which can be defined as

$$u_{PD} = k_p e + k_d \dot{e} \qquad (8)$$

$$u_{PID} = k_p e + k_i \int_0^t e \, d\tau + k_d \dot{e} \qquad (9)$$

where k_p, k_i, k_d, and u are the gain of proportional, integral, derivative, and EHA system's control signal, respectively. The signal of error, e, is identified as

$$e = r - y \qquad (10)$$

where r is the signal of the desired trajectory. Then, the 3rd differentiation of Eq. (10) becomes,

$$\dddot{e} = \dddot{r} - \dddot{y} \qquad (11)$$

B. SMCPD controller design

In this section, the fundamental design of the SMCPD controller is presented. The proportional and derivative sliding surface, s, for the third-order EHA system is considered as follows:

$$s = \left(k_p + k_d \frac{d}{dt}\right)^{n-1} e \qquad (12)$$

where n is the order of EHA system, Eq. (12) becomes,

$$s = k_p^2 e + 2k_P k_d \dot{e} + k_d^2 \ddot{e} \qquad (13)$$

Then, the differentiation of Eq. (13) becomes,

$$\dot{s} = k_p^2 \dot{e} + 2k_P k_d \ddot{e} + k_d^2 \dddot{e} \qquad (14)$$

Incorporating Eq. (11), Eq. (14) becomes,

$$\dot{s} = k_p^2 \dot{e} + 2k_P k_d \ddot{e} + k_d^2 (\dddot{r} - \dddot{y}) \qquad (15)$$

With the use of a reaching law, the system output is compelled to follow the surface under consideration. In order to ensure the stability of the closed-loop system, the reaching law must be developed in such a manner that it meets certain criteria. The exponential law, as shown in Eq. (16), is used in the proposed investigation.

$$\dot{s} = -\epsilon sgn(s) - ks; \; \epsilon > 0, k > 0 \qquad (16)$$

where ε and k are constants.

When the SMC controller is operated, it causes a fast oscillation phenomenon known as "chattering" at the controller output due to a discontinuity in the *signum* function that occurs during control action. In order to overcome this obstacle, the modified *sigmoid* function (17) is employed in the present work instead of the *signum* function.

$$sigmoid(s) = \frac{2}{1 + e^{-\theta s}} - 1 \qquad (17)$$

$$\begin{aligned} sigmoid(s) &> 0; \quad s > 0 \\ sigmoid(s) &= 0; \quad s = 0 \\ sigmoid(s) &< 0; \quad s < 0 \end{aligned} \qquad (18)$$

Incorporating Eq. (16), Eq. (17) becomes,

$$\dot{s} = -\epsilon sigmoid(s) - ks; \; \epsilon > 0, k > 0 \qquad (19)$$

Then, solving for Eq. (6), (15), and (19), the control signal of SMCPD becomes,

$$\begin{aligned} u_{SMCPD} = {}& \frac{k_p^2}{a_1 k_d^2} \dot{e} + \frac{2k_p}{a_1 k_d} \ddot{e} + \frac{1}{a_1} (\dddot{r} + a_2 \ddot{y} \\ & + a_3 \dot{y}) \\ & + \frac{1}{a_1 k_d^2} (\epsilon sigmoid(s) + ks) \end{aligned} \qquad (20)$$

C. SMCPID controller design

This section discusses the fundamental design of the SMCPID controller. The proportional, integral, and derivative sliding surfaces (s) for the third-order EHA system are as follows:

$$s = \left(k_p + k_i \int dt + k_d \frac{d}{dt}\right)^{n-1} e \qquad (20)$$

where n is the order of EHA system, Eq. (20) becomes,

$$\begin{aligned} s = {}& k_p^2 e + 2k_p k_i \int edt + 2k_p k_d \dot{e} + 2k_d k_i e \\ & + k_i^2 \left(\int edt\right)^2 + k_d^2 \ddot{e} \end{aligned} \qquad (22)$$

Then, the differentiation of Eq. (22) becomes,

$$\begin{aligned} \dot{s} = {}& k_p^2 \dot{e} + 2k_p k_i e + 2k_p k_d \ddot{e} + 2k_d k_i \dot{e} \\ & + k_i^2 \int edt + k_d^2 \dddot{e} \end{aligned} \qquad (23)$$

Incorporating Eq. (11), Eq. (23) becomes,

$$\begin{aligned} \dot{s} = {}& k_p^2 \dot{e} + 2k_p k_i e + 2k_p k_d \ddot{e} + 2k_d k_i \dot{e} \\ & + k_i^2 \int edt + k_d^2 (\dddot{r} - \dddot{y}) \end{aligned} \qquad (24)$$

Then, solving for Eq. (6), (19), and (24), the control signal of SMCPID is produced,

$$\begin{aligned} u_{SMCPID} = {}& \frac{\dddot{y} + a_2 \ddot{y} + a_3 \dot{y}}{a_1} + \frac{2k_p \ddot{e} + 2k_i \dot{e}}{a_1 k_d} \\ & + \frac{1}{a_1 k_d^2} [k_p^2 \dot{e} + 2k_p k_i e \\ & + k_i^2 \int edt + \epsilon sigmoid(s) \\ & + ks] \end{aligned} \qquad (25)$$

D. Stability analysis using Lyapunov criteria

The primary goal of SMC controller design is to ensure that the feedback control system is always stable in its overall operation. It is predicted by the Lyapunov stability theorem: the whole system will be stable and will approach the sliding surface when the condition $s\dot{s} < 0$ is satisfied. In this present work, the Lyapunov function is denoted as

$$V = \frac{1}{2} s^2 \qquad (26)$$

$$\dot{V} = s\dot{s} \qquad (27)$$

Substituting Eq. (19) into Eq. (27) becomes,

$$\dot{V} = -s(\epsilon sigmoid(s) + ks); \ \varepsilon > 0, k > 0 \qquad (28)$$

When $s > 0$ and $sigmoid(s) > 0$, Eq. (28) becomes,

$$\dot{V} = -s(\epsilon sigmoid(s) + ks) < 0 \qquad (29)$$

As shown by Eq. (29), $\dot{V} < 0$, which asserts that the designed controller for the exponential reaching rule will be stable for $s > 0$.

When $s < 0$ and $sigmoid(s) < 0$, let $s = -\emptyset$ and $sigmoid(-\emptyset) = -\partial$, Eq. (28) becomes,

$$\dot{V} = -(-\emptyset)(\epsilon(-\partial) + k(-\emptyset)) < 0 \qquad (30)$$

As shown by Eq. (30), $\dot{V} < 0$, which asserts that the designed controller for the exponential reaching rule will be stable for $s < 0$.

Based on Eq. (29) and (30), the Lyapunov stability theory is being used to guide the design of SMCPD and SMCPID controllers for third-order double-acting EHA systems, and the system output will be bound when the input is bounded.

E. Gain optimization for controllers through the PSO algorithm

The PSO can be utilized to obtain optimum values of the design variables, and its algorithm was designed by mimicking the swarm social behavior of bird flocking and fish schooling. A swarm of individuals called particles moves through a high-dimensional search space among the entire population towards the global optimal (minimum or maximum) solution with a specific position and velocity. Each particle in the swarm offers a great solution and adheres to a simple principle by replicating its own previous success. Furthermore, the personal best position in a neighborhood influences the position of particle and the optimal solution among the personal best positions is known as the global best position. Essentially, the PSO algorithm's implementation may be described as shown in Fig. 4. In the current work, the particle population size, maximum iteration, and cognitive and social coefficients are all set to 20, 50, 2, and 2, respectively.
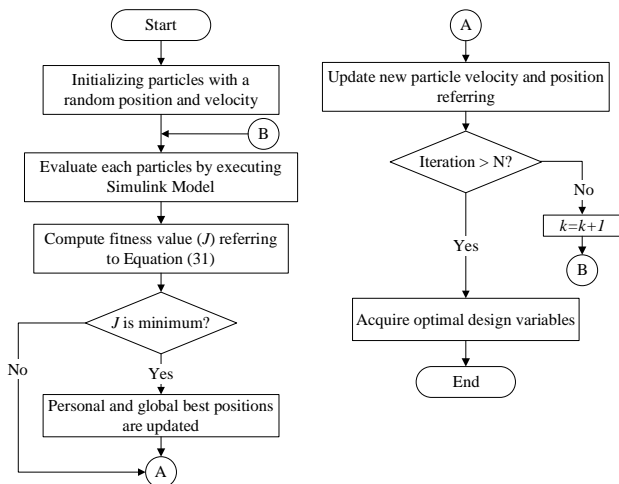

Fig. 4. The overall design process of using PSO algorithm

$$J = \sum |e(t)| \qquad (31)$$

F. Performance Evaluation Criteria

a) Rejection of noise disturbances: One of the most important objectives of a good control algorithm is to appropriately reject undesirable disruption so that the planned path may run without interruption. In the present study, the Simulink Band-Limited White Noise disturbance signal with 0.00002 of noise power and 0.1 of sampling time is considered.

b) Mean Square Error (MSE): MSE disqualifies large-valued errors over small-valued errors, which reflect overshoot and aggressive control. In the present study, the magnitude of chattering phenomenon is considered relatively proportional to the MSE magnitude.

$$MSE = \frac{1}{n}\sum_{t=0}^{T}\left(e(t)\right)^2 \qquad (32)$$

IV. SIMULATION RESULT AND DISCUSSION

The simulated evaluation of trajectory tracking performance for the PD, PID, SMCPD, and SMCPID controllers using MATLAB/Simulink (R2021b) with 1 ms of sampling time and optimized parameters using PSO is shown in this section. The controllers used are the PD, PID, SMCPD, and SMCPID controllers. As an additional feature, the sine signal is used to create the required trajectory. The values of a_1, a_2, and a_3 are taken into consideration to be 144400, 3.723, and 7855, respectively, and these values are acquired by the system identification process. Meanwhile, the details of parameters for all controllers, which were obtained using the PSO algorithm, are listed in Table II.

TABLE II. OPTIMIZED PARAMETERS VALUE USING PSO

Controllers	Parameter					
	k_p	k_d	k_i	ε	k	θ
PD	58.91	1.92	-	-	-	-
PID	51.53	1.75	37.58	-	-	-
SMCPD	57.97	0.23	-	2.16	9.36	0.85
SMCPID	55.82	0.25	33.63	2.39	9.57	0.57

A thorough investigation was carried out, and the results are shown in Table III, where the mean square error (MSE) values are calculated. It is possible to infer from the data that the SMCPID, SMCPD, and PID controllers improve MSE without the presence of noise disturbance by 91.51%, 85.47%, and 28.01%, respectively, over the PD controller.

TABLE III. MSE VALUES

Controller	MSE ($\times 10^{-4}$)	
	Without noise disturbance	With noise disturbance
PD	55.34	55.35
PID	39.84	39.86
SMCPD	8.04	9.08
SMCPID	4.70	6.63

In the presence of noise disturbances, the SMCPID, SMCPD, and PID controllers outperform the PD controller by 88.03 %, 83.59 %, and 27.99 %, respectively. Furthermore, the performance of the SMCPID, SMCPD, PID, and PD controllers diminishes in the presence of noise disturbance. Meanwhile, in Figs. 5–10, a trajectory tracking task, the related controller output, and error curves are shown, confirming the superiority of the SMCPID controller over the other controllers in terms of performance and accuracy.
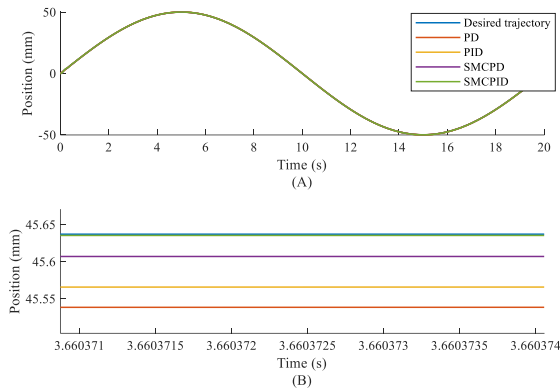
Fig. 5.   Trajectory tracking without noise signal; (A) Origin and (B) zoom
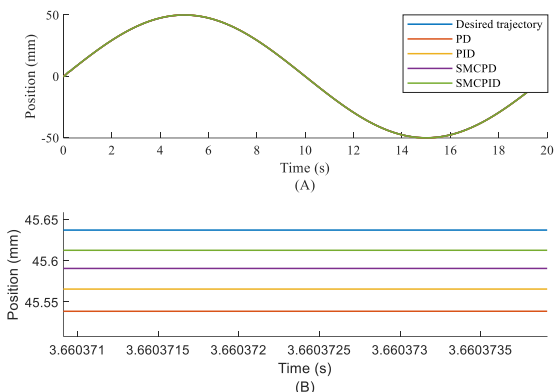
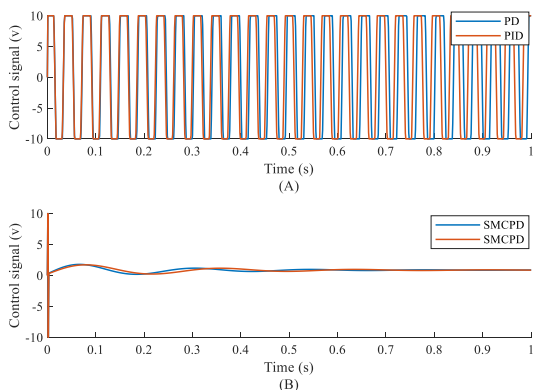Fig. 6.   Trajectory tracking with noise signal; (A) Origin and (B) zoom

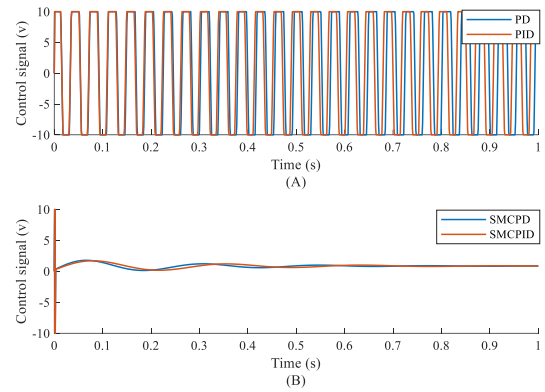Fig. 7.   Corresponding controller output signal without noise signal

Fig. 8.   Corresponding controller output signal with noise signal

Fig. 9 depicts the error signals that were generated for the individual controllers without the presence of noise interference. There are bigger errors in the PD and PID controllers shown in Fig. 9(A) and Fig. 9(B) than there are in the SMCPD and SMCPID controllers, which are shown in Fig. 9(C) and Fig. 9(D).
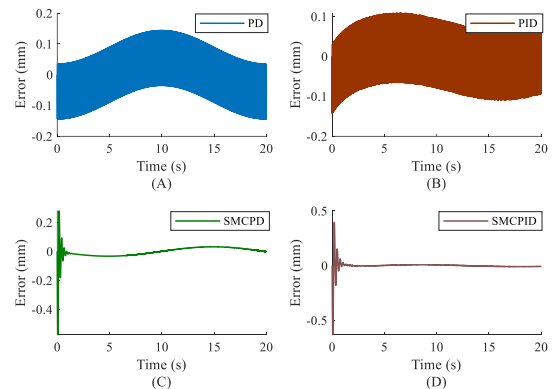
Fig. 9.   Corresponding error signal without noise signal

In addition, Fig. 10 shows the generated error signals with noise interference for the individual controllers. The PD and PID controllers, in comparison to the SMCPD and SMCPID controllers, nevertheless exhibit bigger errors. When comparing Fig. 9(C) and Fig. 10(C) and Fig. 9(D) and Fig. 10(D), however, it is evident that there are large ripples in Fig. 10(C) and Fig. 10(D). It is caused by the interference of noise signals, which causes this phenomenon to occur.
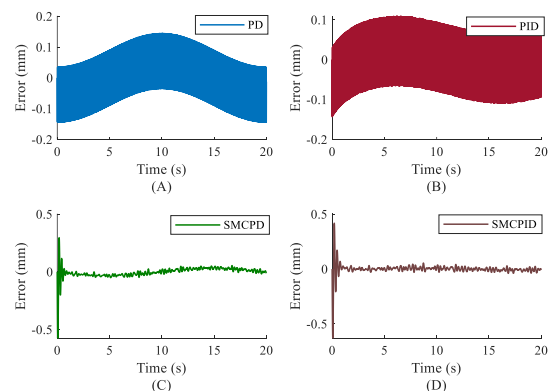
Fig. 10. Corresponding error signal with noise signal

The SMC provides more convenient and better performance in trajectory tracking control based on MSE analyses, controller efforts, and tracking performance observations. It also ensures that the control system is stable. In Fig. 11, the sliding surface shows that the system has entered the sliding phase and will stay there until it reaches the equilibrium point, at which point the error and derivative of error approach zero even in the presence of noise disturbance.
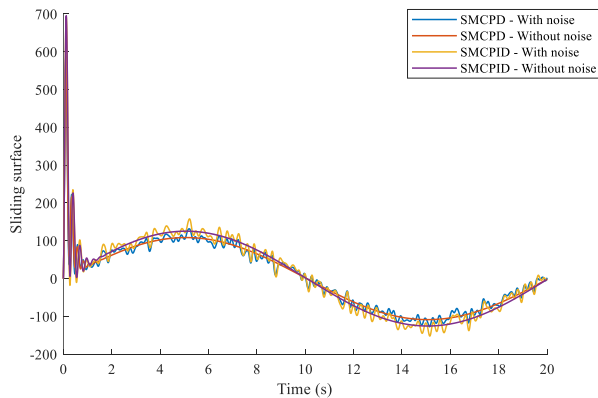

Fig. 11. Corresponding sliding surface signals

V. CONCLUSION AND RECOMMENDATION

It is shown in this paper that nonlinear double-acting electrohydraulic actuator (EHA) systems can be controlled using PD, PID, and PD sliding mode (SMCPD) controllers, as well as PID sliding mode (SMCPID). The performance of controllers is evaluated in the context of trajectory tracking tasks and disturbance rejection tasks, respectively. Chattering is a key problem that must be handled in a traditional sliding mode controller (SMC). This issue is easily solved by substituting the signum function with a modified sigmoid function. The SMC controllers are built with exponential law in mind, ensuring that the entire system is stable on the basis of Lyapunov's law. The sum of square errors was used to calculate the overall performance index. PSO is in charge of tuning the gains of the controllers. The simulated results obtained indicate that the SMCPID controller outperforms the PD, PID, and SMCPD controllers in all of the performance characteristics tested throughout the controller assessment process. It is necessary to test the performance of the suggested controller on a hardware platform that operates in real-time in the future, as well as experiment with various SMC versions, such as fractional order SMCs and fuzzy PID controllers, which may be explored further in this work.

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