Journal of Autonomous Intelligence (2024) Volume 7 Issue 3
doi: 10.32629/jai.v7i3.1162

ORIGINAL RESEARCH ARTICLE

Performance improvement of DC servo motor using sliding mode controller

Mahendra K. Dawane[1,*], G. M. Malwatkar[1], Suhas P. Deshmukh[2]

[1] *Department of Instrumentation Engineering, Government College of Engineering, Jalgaon 425002, India*

[2] *Department of Mechanical Engineering, Government College of Engineering, Karad 415124, India*

*** Corresponding author:** Mahendra K. Dawane, mahendra.dawane@dtemaharashtra.gov.in

ABSTRACT

Sliding mode control has emerged as a valuable technique for enhancing dynamic response in various fields, including load frequency regulation and remote vehicle applications. While the widely adopted PID controller has proven effective for optimizing control tasks in industries, sliding mode control offers distinct advantages. By controlling the slope of the dynamical trends of state variable behavior, it enables rapid dynamic response with minimal or no overshoot, as well as negligible steady-state error. The robustness of sliding mode control, which makes it highly resilient to changes in plant parameters and outside disturbances, is one of its main advantages. A digital computer simulation was run using Simulink in the MATLAB software, concentrating on a position control system using an armature voltage-controlled D.C. servo motor to assess how well it performed. To learn more about the operation of sliding mode control, several control laws were used and state trajectories were examined. When compared to the conventional tuned PID control, the findings and discussion conclusively show sliding mode control to be more successful. The sliding mode technique has exceptional effectiveness, including enhanced dynamic response, less overshoot, and almost no steady-state error. Furthermore, its robust nature ensures consistent operation even in the face of parameter fluctuations and external disturbances. This study underscores the immense potential of sliding mode control as a powerful alternative to conventional control methods. Its ability to enhance system performance, coupled with its inherent robustness, makes it a compelling choice for various industrial applications where precise control and resilient operation are crucial.

Keywords: sliding mode control; position servo system; armature-controlled DC motor; robust control; dynamic response; overshoot reduction

ARTICLE INFO

Received: 20 August 2023
Accepted: 6 November 2023
Available online: 29 December 2023

1. Introduction

In the ever-evolving landscape of control systems, engineers and researchers continually seek innovative approaches to enhance the performance and resilience of industrial applications. One such powerful and robust control technique that has garnered significant attention is Sliding Mode Control (SMC). Emelyanov and his associates in the Soviet Union first developed and thoroughly investigated SMC in the early 1950s. SMC has made great progress since then and has found use in a range of systems, including nonlinear, multi-input-multi-output, discrete, and stochastic models. Sliding Mode Control is composed of three distinct stages: reaching mode, sliding mode, and steady-state mode. By using a reaching law differential equation in the reaching space, the control problem is transformed into a discrete sliding surface in the reaching mode[1]. Once the system has reached the sliding surface and entered the sliding mode, the dynamics are still unaffected by modelling errors or external perturbations. The steady-state mode then takes on a variety of shapes as it works to keep the necessary condition along the sliding surface[2].

The advantages of Sliding Mode Control over traditional control methods have garnered considerable interest among researchers and engineers alike. Its exceptional robustness and ability to maintain stability in the presence of uncertainties and disturbances make it highly desirable for applications requiring precise and resilient control. In industrial settings, where variations in system parameters, external disturbances, and load changes are common, the robustness of SMC is particularly valuable for ensuring safety, efficiency, and reliability[3,4]. One of the most significant benefits of SMC is its high accuracy in controlling the system's behavior, leading to minimal error between the desired state and the actual state. This precision is crucial for various applications, such as robotics and motion control systems, where accurate positioning and control are paramount. Moreover, systems under SMC exhibit rapid dynamic responses, enabling swift and efficient control actions. This attribute is particularly advantageous for time-critical processes where quick responses are essential for optimal performance[5].

Stability is a critical aspect of control systems, and traditional control techniques may struggle to maintain stability in the face of uncertainties, leading to performance degradation or instability. In contrast, SMC is designed to ensure stability even in the presence of variations in system parameters, making it a reliable choice for various industrial applications. In addition to its robustness and accuracy, the simplicity of the design and implementation of SMC has further contributed to its widespread adoption. Compared to more complex control techniques, the straightforward nature of SMC reduces development time and costs, making it accessible for a wide range of applications and industries[6].

Over the years, Sliding Mode Control has found applications in various industrial domains. In variable speed drives and power converters, SMC's robustness and ability to handle uncertainties make it an attractive choice, ensuring stable and efficient operation while contributing to enhanced energy efficiency[7]. In robotics and automation, precise control of motion and positioning is crucial, and SMC's ability to deliver accurate control with minimal error is highly advantageous in such applications. The aerospace and aviation industries also benefit from SMC's robustness and resilience. In safety-critical applications involving aircraft, spacecraft, and unmanned aerial vehicles (UAVs), stable and precise control is essential for mission success and passenger safety, making SMC a promising control strategy in these fields[8].

The theoretical underpinnings of sliding mode control will be covered in detail in the sections that follow, along with its benefits over conventional control techniques, applications in industrial systems, and simulation and analysis results of SMC in the context of position control using an armature-controlled DC motor. With this research, we intend to add to the body of knowledge on SMC and demonstrate how it has the potential to completely alter the field of control systems, particularly in the context of industrial applications[9].

The sliding mode controller (SMC) has a number of noteworthy advantages, such as resilience to modeling errors, robustness, and quick dynamic response. It is not without limitations, though. Chattering, which is defined as the abrupt and occasionally excessive switching of control actions close to the sliding surface, is a major drawback that can cause unwanted noise and mechanical wear in physical systems. Furthermore, because SMC's non-smooth nature can lead to abrupt changes in control input, it is less appropriate for applications where small, gradual control adjustments are necessary or where taking sudden action could be harmful. Compared to PID control, tuning SMC parameters can be more complex and time-consuming because it involves changing things like the sliding surface slope and feedback gains. For some applications, SMC may be less accessible due to its complexity. Moreover, even though SMC is robust, it might not be the best choice for systems with accurate modeling available because it might be difficult to fine-tune. Because PID control has smoother control input, integral action, and is simpler to implement, it is still the preferred option when linearity, steady-state error minimization, low noise, or simplicity is critical[10,11].

When compared to PID control, SMC frequently has a higher computational complexity and may need more computing power. However, when the unique benefits of SMC like robustness and dynamic response are critical to the success of the application, then this added complexity may be justified. When selecting one of these control strategies, it is imperative to take into account the computational trade-offs in light of the system’s requirements and resources[12,13].

A sliding mode controller (SMC) is more cost-effective to implement than PID control when both hardware and software factors are taken into account. Because of its intricate control algorithm, SMC typically requires more computational power from the hardware, possibly requiring specialized hardware or more powerful processors. This may lead to increased initial hardware expenses. Software-wise, SMC might need more complex design and tuning, which would raise the cost of development and upkeep. PID control, on the other hand, is more affordable in terms of both hardware and software since it is easier to implement and requires less computing power. The decision is dependent on the particular application requirements, though, as SMC’s advantages in terms of robustness and precision of control may outweigh the increased costs for systems where accuracy and dependability are critical[14].

With DC motors, sliding mode control can improve energy efficiency. It enhances DC motor efficiency by reducing steady-state errors and offering precise control. This is beneficial for applications where energy conservation is a top concern because it can lead to lower energy consumption and increased overall energy efficiency. By taking advantage of its built-in robustness, the sliding mode controller (SMC) in a position servo system manages external disturbances. SMC preserves the state of the system on a sliding surface in order to dynamically adapt to disturbances[15]. The control action quickly modifies to keep the system on the sliding surface when disturbances impact it, guaranteeing that the intended control response is maintained. The secret here is that SMC is resilient to uncertainties and disturbances because it does not rely on an exact model of the system. The controller keeps an eye out for disruptions and adjusts accordingly, enabling the system to continue operating as intended even in the face of external influences. SMC’s resilience to external disruptions is a significant benefit for control systems. The importance of Sliding Mode Control (SMC) as a potent substitute for traditional control techniques is emphasized in this paper. It demonstrates how SMC can significantly improve system performance while maintaining its inherent robustness, which makes it an appealing option for a variety of industrial applications where accurate control and reliable operation are essential[16].

Challenges in implementing sliding mode control in real systems

When applying SMC in real systems, it is crucial to address issues with chattering, actuator constraints, model uncertainties, control effort, and tuning complexity. SMC provides robustness and precise control. The design and implementation processes need to take these constraints into careful consideration[17].

a. Chattering: Chattering, or the abrupt switching of control actions close to the sliding surface, is one of the main problems with SMC. In physical systems, this chattering can result in increased energy consumption and mechanical wear.
b. Actuator Constraints: Actuator restrictions and limitations can have an impact on SMC. The speed, accuracy, and range constraints of real-world actuators may have an impact on SMC performance.
c. Model Uncertainties: SMC depends on accurate understanding of the dynamics of the system. The robustness of the controller may be tested in real-world systems due to modeling uncertainties, parameter variations, and external disturbances.

d. High Control Effort: SMC can sometimes demand high control effort, which might not be feasible or desirable in applications where energy efficiency is crucial.

e. Tuning Complexity: For real-time applications, tuning SMC parameters like the sliding surface slope and feedback gains can be difficult and time-consuming.

When applying SMC in real systems, it is crucial to address issues with chattering, actuator constraints, model uncertainties, control effort, and tuning complexity. SMC provides robustness and precise control. The design and implementation processes need to take these constraints into careful consideration.

2. The armature voltage controlled D.C. motor position servo mechanism

The position control system is designed to achieve accurate positioning of the output shaft, driven by a DC motor with armature voltage control. The system’s schematic diagram is depicted in **Figure 1**. Two potentiometers are integrated into the system to convert the input and output positions into proportionate electric signals. These potentiometers play a crucial role in providing feedback to the control system. When the system is in operation, the input position signal and the output position signal are compared. The difference between these two signals represents the error signal, indicating the deviation between the desired position and the actual position of the output shaft. To amplify the error signal, an amplifier with a gain factor KA is utilized. The amplified error signal is then fed into the armature circuit of the DC motor. In the position control system, the field winding of the DC motor is excited with a constant voltage. When the system detects any error between the desired and actual positions, the DC motor generates a torque in response to the amplified error signal.

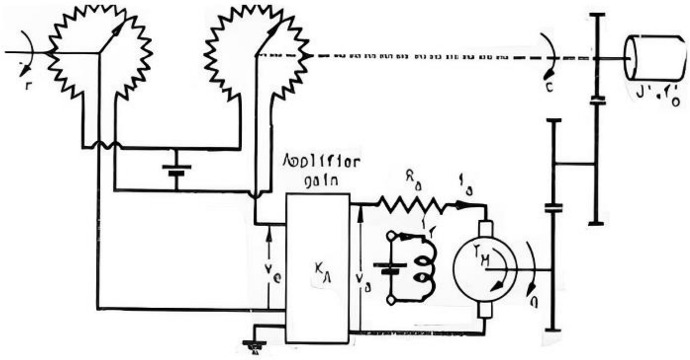

Figure 1. Schematic diagram of DC position control system.

The transmitted torque from the motor is then transferred to the output shaft through a gear train. This torque rotates the output shaft in such a direction as to minimize the error and bring the shaft closer to the desired position. As the output shaft approaches the desired position, the error signal diminishes, and the motor’s torque reduces accordingly. This process continues until the error signal is reduced to zero, indicating that the output shaft has reached the desired position. The position control system using an armature voltage-controlled DC motor is widely utilized in various applications requiring precise and accurate positioning. By providing feedback and adjusting the motor’s armature voltage, the system ensures that the output shaft follows the desired position, even in the presence of disturbances or external factors[18,19]. The simplicity and effectiveness of this control system make it a popular choice in industrial settings, robotics, automation, and other fields where precise positioning and control are essential for optimal performance and efficiency. The ability of the system to respond swiftly to deviations in position, and its capacity to maintain stable operation, contribute to its widespread application across various industries[17].

Every control system component of servo position control system is modelled using its governing differential equation and practical application involves several constants used for such components.

Following are the constants which are related to feasibility of above-described scheme shown in **Figure 2**.

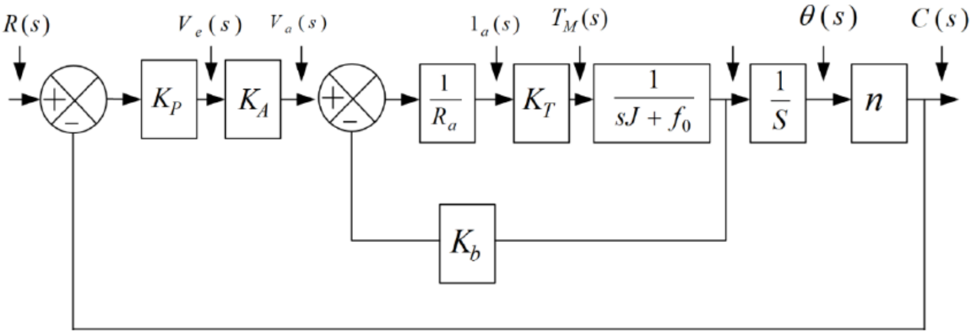

Figure 2. Mathematical model of servo scheme.

Kp: Potentiometer Constant;

KA: Amplifier Gain;

Ra: Armature resistance of d.c. motor;

IA: Armature current;

TM: Motor torque;

θ: Angular speed;

θ: Position.

3. Position servo system design of the sliding mode controller

The positional discrepancy and its differential are expressed as fundamental parameters, transforming the kinetic equations. The goal of this adaptation is to create a positional regulator with characteristics of gliding method. Regulating the controller configuration on either side of the gliding axis, designated as S, is the fundamental component of controlling the gliding mode. The positional discrepancies' trajectory is forced by this correction to converge on the phase diagram's origin. This gliding axis S's gradient is equal to l/Tc, where Tc stands for the temporal constant of the gliding mode's reaction to differences. While choosing a lower Tc value speeds up dynamic responsiveness, it might increase the time it takes the trajectory to link with the glide axis, thus resulting in a reduction in robustness. To reduce constant-state differences brought on by disturbances Ti, the technique incorporates feedback amplification factors, designated as a1 and a2, together with a perturbation amplification, indicated as d. These elements work together to carefully calibrate the positioning regulator, which improves its functionality. The formation of gliding mode behaviour depends on the satisfaction of particular requirements. These conditions primarily deal with the fundamental parameters' trajectories, which consistently point in the direction of the gliding axis S. When compared to traditional PID regulators, the system is better able to steer the servo-based positional management along the intended trajectory because of this orientation. The requirement that the slope of the gliding axis must continue to be submissive to the unfavourable eigenvalue of the system's characteristic equation results in a minimum threshold for Tc in the pursuit of the ultimate design. This requirement ensures consistency and reliable control over the system's activities.

In comparison to conventional PID controllers, the position controller demonstrates improved performance characteristics by adding these sliding mode qualities. In a variety of real-world applications, the ability to converge error paths towards the phase plane's origin enhances control accuracy and effectiveness. Additionally, the addition of dither gain and feedback gain coefficients enhances the position control system's overall reliability by enabling higher adaptation and robustness against disturbances. The ability of the sliding mode controller to direct the servo position control down the desired path leads to more precise and reliable control responses as compared to conventional PID controllers. This advantage makes it a preferred choice in various industrial applications, such as robotics, automation, and motion control systems, where precise positioning and stable performance are essential. As researchers and engineers continue to explore the potential of sliding mode control in position control systems, the fine-tuning of parameters, such as Tc and feedback gains, will be instrumental in optimizing performance for specific applications. The versatility and robustness of sliding mode control open up new possibilities for efficient and reliable control strategies, contributing to advancements in various fields of engineering and technology. Furthermore, ongoing research and development in sliding mode control techniques will likely uncover further refinements, enabling even more sophisticated applications and extending the reach of this control methodology to various industries and sectors. As advancements in control theory continue to evolve, sliding mode control with its unique properties remains an exciting and promising area of study, poised to drive innovation in control systems and contribute to a wide range of practical applications.

Tuning feedback gain coefficients (a1 and a2) and the dither gain (d) in a sliding mode controller involves a process of adjusting these parameters to optimize the control system’s performance. The feedback gain coefficients, a1 and a2, are responsible for shaping the controller’s response to errors and disturbances. Tuning them aims to strike a balance between achieving a rapid response and minimal overshoot while maintaining robustness against disturbances. This process often requires experimentation and iterative adjustments.

On the other hand, the dither gain (d) introduces small, high-frequency oscillations in the control signal to eliminate steady-state error resulting from friction and other sources. Tuning the dither gain involves selecting its magnitude carefully to effectively reduce steady-state error without introducing undesirable noise or instability. Ultimately, the specific values of a1, a2, and d depend on the characteristics of the controlled system and the desired performance criteria. This tuning process may involve trial-and-error methods or more sophisticated optimization techniques to fine-tune the parameters for optimal control system behavior[20].

Design of the sliding mode controller for position servo system

The equations of motion (1)–(3) are recast using the position error and its derivative as crucial state variables in order to create a position controller with sliding mode features. The purpose of this strategic shift is to maximize the advantages of c in maintaining target positions. The resulting controller is prepared to provide increased stability and responsiveness thanks to this creative adaption of state variables, giving it a promising path for strengthening control techniques in pertinent applications:

$$X_1 = \theta^* - \theta \tag{1}$$

$$\dot{X}_1 = -\theta = -\omega = X_2 \tag{2}$$

$$\dot{X}_2 = -\dot{\omega} = \frac{T_e - T_l - B\omega}{J} \tag{3}$$

To produce the control signal Iaw and specifically achieve a transient response for the position error x1, a state variable feedback controller must be designed. Both the numerous plant characteristics, such as J, B, and Kt, as well as the external disturbances Ti, should have no impact on the ideal dynamics of this response. This is done by introducing the idea of sliding mode control, which entails creating a sliding mode along line S in the phase plane[21]. The sliding mode is described by a certain equation, and its application makes sure that the position error trajectory follows this sliding line and eventually converges to the phase plane’s origin. The sliding mode’s capacity to control the system’s behaviour independently of outside influences and system characteristics enables it to achieve the required dynamics for the position error x1. This sliding mode control strategy provides stability and resilience, which makes it a useful method for achieving precise and dependable control in a variety of real-world applications. This is achieved by introducing the sliding mode along line S in the phase plane as given by

$$S = X_1 + T_C \dot{X}_1$$

Sliding mode control is a unique method that dynamically restructures the controller along the entire range of the sliding threshold, S. The complex path of positional discrepancy needs to be recalibrated before it can align with the sliding threshold, travel it, and ultimately come to rest at the origin of the phase plane. A crucial parameter in this context is l/Tc, which provides information about the slope of the sliding threshold and denotes the temporal constant regulating error handling during sliding mode operation. Lowering Tc causes the system to become more dynamic and agile, which causes a quick response that moves the system swiftly in the direction of the sliding threshold. This benefit, however, is at the expense of a longer travel time to the sliding line, which results in a slight reduction in robustness. Thus, the choice of Tc involves striking a balance between achieving a rapid dynamic response and ensuring a sufficient level of robustness in the control system[22].

The sliding mode control's capability to direct the trajectory of the positional error towards the sliding line, regardless of disturbances or system parameters, makes it an attractive and robust control strategy. This resilience is particularly valuable in practical applications where uncertainties and variations in the system can occur. Despite the potential trade-off between dynamic response and robustness when selecting Tc, the sliding mode control remains a promising and effective method for precise and stable control in various engineering fields. Its ability to guide the system's behavior along the sliding line allows for accurate and reliable positioning, making it a preferred choice in industries where precise control is crucial for optimal performance and efficiency. Furthermore, ongoing research and advancements in sliding mode control techniques may lead to further improvements, enabling its application to even more complex and challenging control scenarios. The adaptability and versatility of sliding mode control continue to attract interest from researchers and engineers, with the potential to reshape the future of control systems in diverse fields of engineering and technology[23].

Let the control I be given by

$$\begin{array}{ll} L = a_1 p_1 X_1 + a_2 p_2 X_2 + d \ \text{sgn(S)} & \\ p_1 = 1 & \text{for } \ \mathrm{S}X_1 > 0 \\ p_1 = -1 & \text{for } \ \mathrm{S}X_1 < 0 \\ p_2 = 1 & \text{for } \ \mathrm{S}X_2 > 0 \\ p_2 = -1 & \text{for } \ \mathrm{S}X_2 < 0 \\ \operatorname{sgn}(S) = 1 & \text{for } \ S > 0 \\ \operatorname{sgn}(S) = -1 & \text{for } \ S < 0 \end{array}$$

a1, a2: feedback gain coefficients,

d: dither gain to eliminate steady state error due to disturbance.

Control law can be understood by architecture as shown in **Figure 3** where each equation is implemented in the form of block diagram.

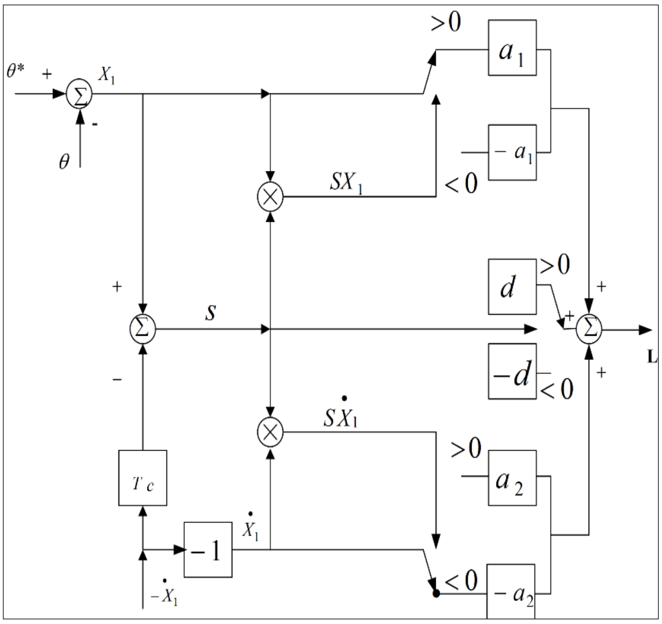

Figure 3. Architecture of SLMC based Control Law.

4. Simulation results

MATLAB-Simulink is a widely used software environment for numerical computing, modeling, and simulation. MATLAB is a high-level programming language that's particularly popular in engineering, science, and mathematical disciplines. Simulink, an extension of MATLAB, provides a graphical interface for modeling, simulating, and analyzing dynamic systems, making it especially suitable for control system design, signal processing, and other multidomain simulation tasks. Engineers and researchers use this integrated environment to build models, run simulations, and analyze results efficiently.

In this study, we conducted a thorough simulation to evaluate the performance of the position servo system coupled with a sliding mode control rule using the MATLAB-SIMULINK environment. The auxiliary section presents the controller and equipment parameters utilized in the simulation, offering a point of comparison. The simulation results show the enormous gains in system responsiveness obtained by the sliding mode controller over the conventional control technique. Using a range of varied sliding line inclination values, we investigated the system's behavior for a positional shift of a substantial scale both with and without the sliding mode controller. The dynamic character of sliding mode control is amply illustrated by the phase plane trajectory mapping of speed vs position as shown in **Figure 4**. This trajectory reveals a distinctive pattern that emphasizes the sliding mode's capacity to expertly and successfully guide the system in the intended path. Despite pauses or modifications to the system settings, slider mode control has the natural capacity to retain constant and precise command. Location and speed's temporal response also provide details about how the system is functioning. The sliding mode controller creates less oscillations and has a quicker stabilization time than a traditional PID controller.

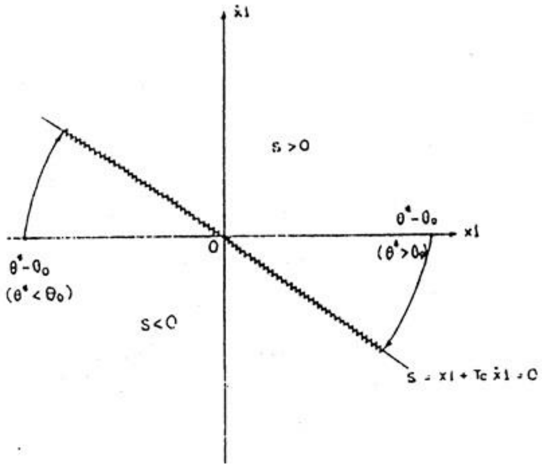

Figure 4. Phase plane trajectory of positional error in sliding mode.

This improvement in performance is particularly significant in applications where precise and rapid positioning is crucial for optimal system operation. While conventional PID controllers can be tuned to optimize their parameters and achieve better outputs, our study reveals that there is still room for improvement through the implementation of sliding mode control. The unique capability of sliding mode control to manipulate the dynamics of the trajectory through control over the slope and reach of the sliding line enhances its potential for achieving superior performance. In summary, the simulation results confirm the effectiveness of the sliding mode controller in enhancing the performance of the position servo system. Its ability to guide the system along the desired trajectory, mitigate disturbances, and reduce settling time makes it a promising and robust control strategy. Furthermore, the flexibility to fine-tune the controller parameters offers opportunities for further optimization and improvement. Sliding mode control represents a valuable advancement in control system design, holding promise for applications in various engineering fields, where precision, stability, and efficiency are paramount.

The reaction of the servo drive to a unit step change in position command is shown in **Figures 5–8** under typical operating conditions. With less overshoot and a quicker response to new commands, the output position response with SLMC is superior than that of a tuned PID Controller. Also effect of design parameter i.e., slope of sliding line is also studied with 10% increment around the optimum point with Tc = 0.18. Based on specifications of user, one can choose different parameters for adjusting performance of SLMC. Tuned PID Controller is a conventional option to meet certain specifications. Sliding mode controller pushes the system to desired performance.

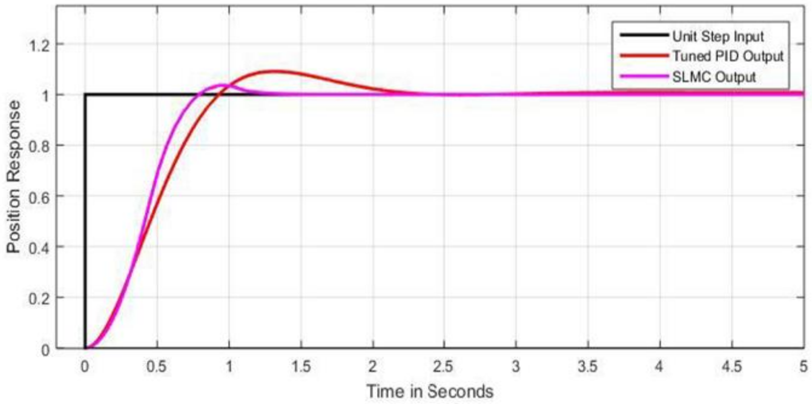

Figure 5. Position response for tuned PID and SLMC for specific slope of sliding line for Tc = 0.18.

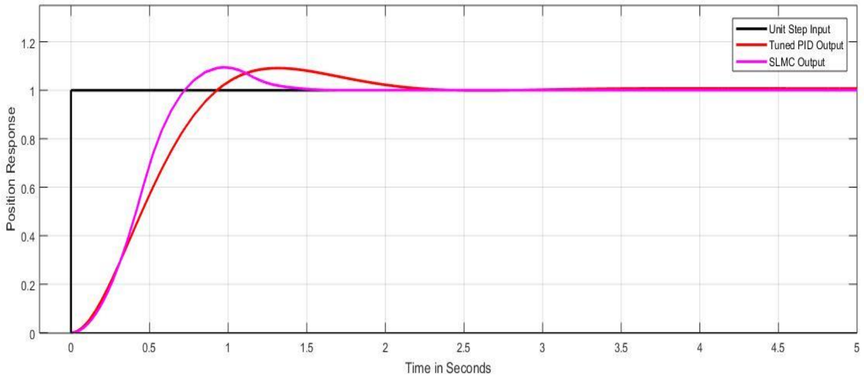

Figure 6. Position response for tuned PID and SLMC and 10% increase in slope of sliding line Tc = 0.162 (10% Less).

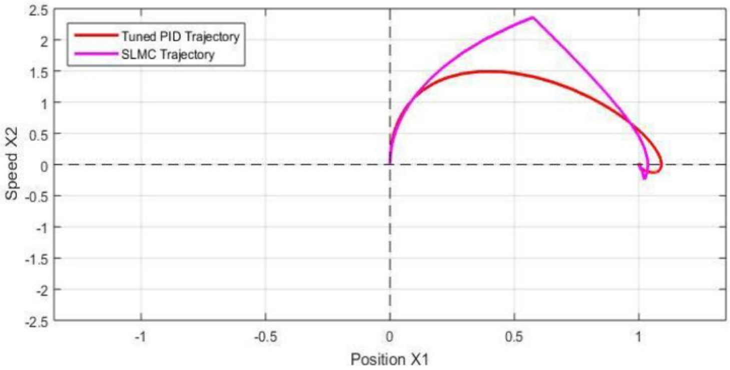

Figure 7. Phase plane trajectory for tuned PID and SLMC for specific slope of sliding line for Tc = 0.18. Tc = 0.162 (10% Less).

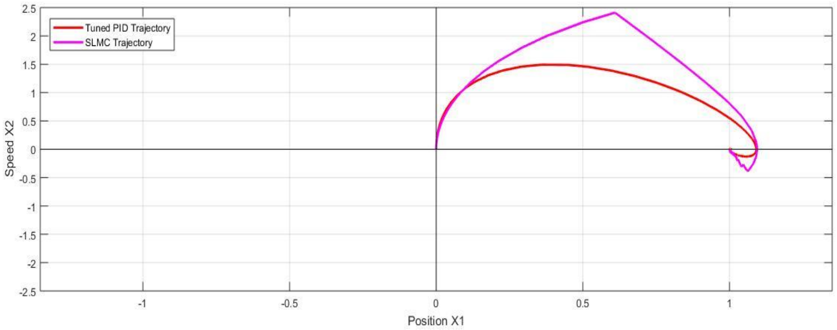

Figure 8. Phase plane trajectory for tuned PID and SLMC and 10% increase in slope of sliding line Tc = 0.162 (10% Less).

5. Conclusion

In this study, a position servo system using an armature-driven DC servo motor is successfully controlled by a sliding mode controller. The outcomes demonstrate several noteworthy advantages of the sliding mode control method. First, the output position response closely resembles a first-order system and exhibits reduced overshoot when compared to alternative control techniques. In situations where accurate and fluid positioning are crucial, this trait is quite advantageous. Furthermore, the sliding mode control shows the capacity to force system states down the sliding line, producing quicker response times. Improved performance in a variety of settings is made possible by this characteristic, which enables improved control over the system's dynamics. Thirdly, the flexibility to adjust the slope of the sliding line by modifying the relevant parameters further enhances the versatility of the sliding mode control approach. This adaptability enables engineers to fine-tune the controller to meet specific performance requirements for different systems. Moreover, the sliding mode control consistently outperforms other controller types in terms of overall performance. Its ability to achieve better stability and dynamic response makes it a favorable choice for precision control applications. The sliding mode controller proves to be an effective and reliable control strategy for the position servo system. Its benefits include reduced overshoot, faster response times, adjustable sliding line parameters, superior performance compared to other controllers, and improved stability and dynamic response. These advantages highlight the potential of sliding mode control in various industrial applications, where precise positioning and robust control are of paramount importance. As further research and development in control theory progress, sliding mode control holds promise for advancing control system design and contributing to various engineering fields.

Author contributions

Conceptualization, MKD; methodology, MKD; software, MKD; validation, MKD; formal analysis, GMM; investigation, GMM; resources, GMM; data curation, SPD; writing—original draft preparation, MKD; writing—reviewing and editing, GMM; visualization, SPD; supervision, GMM; project administration, SPD. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

References

1. Utkin V. Variable structure systems with sliding modes. IEEE Transactions on Automatic Control. 1977, 22(2): 212-222. doi: 10.1109/tac.1977.1101446
2. Dote Y, Takebe M, Ito T. Variable structure control with sliding mode for DC drive speed reguration. 1982 IEEE Power Electronics Specialists conference. 1982. doi: 10.1109/pesc.1982.7072401
3. Harashima F, Hashimoto H, Kondo S. MOSFET Converter-Fed Position Servo System with Sliding Mode Control. IEEE Transactions on Industrial Electronics. 1985, IE-32(3): 238-244. doi: 10.1109/tie.1985.350165
4. Namuduri C, Sen PC. A Servo-Control System Using a Self-Controlled Synchronous Motor (SCSM) with Sliding Mode Controller. IEEE Transactions on Industry Applications. 1987, IA-23(2): 283-295. doi: 10.1109/tia.1987.4504904
5. Hung JY, Gao W, Hung JC. Variable structure control: a survey. IEEE Transactions on Industrial Electronics. 1993, 40(1): 2-22. doi: 10.1109/41.184817
6. Tang WJ, Liu ZT, Wang Q. DC motor speed control based on system identification and PID auto tuning. 2017 36th Chinese Control Conference (CCC). 2017. doi: 10.23919/chicc.2017.80283760
7. Durdu A, Dursun EH. Sliding Mode Control for Position Tracking of Servo System with a Variable Loaded DC Motor. Elektronika ir Elektrotechnika. 2019, 25(4): 8-16. doi: 10.5755/j01.eie.25.4.23964
8. Uppal AA, Azam MR, Iqbal J. Sliding Mode Control in Dynamic Systems. Electronics. 2023, 12(13): 2970. doi: 10.3390/electronics12132970
9. Mezher LS. Characteristics of Servo DC Motor with PID Controller. Journal of Mechanical Engineering Research and Developments. 2021, 44(2): 392-400.
10. Liu J, Peng Q, Huang Z, et al. Enhanced Sliding Mode Control and Online Estimation of Optimal Slip Ratio for Railway Vehicle Braking Systems. International Journal of Precision Engineering and Manufacturing. 2018, 19(5): 655-664. doi: 10.1007/s12541-018-0079-y
11. Ma'arif A, Setiawan NR. Control of DC Motor Using Integral State Feedback and Comparison with PID: Simulation and Arduino Implementation. Journal of Robotics and Control (JRC). 2021, 2(5). doi: 10.18196/jrc.25122.
12. Leal IS, Chamil A, Yasith SP. Design, Simulation, Analysis and Optimization of PID and Fuzzy Based Control Systems for a Quadcopter. Electronics. 2021, 10(18): 2218. doi: 10.3390/electronics10182218
13. Aydin MN, Coban R. Sliding mode control design and experimental application to an electromechanical plant. 2016 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON). 2016. doi: 10.1109/rtucon.2016.7763076
14. Boonsing S, Kaewpradit P. Comparison of PI and PID control performances coupled with Kalman Filter for DC motor speed control via MATLAB/Simulink. Engineering Journal Chiang Mai University. 2021, 28(1): 195-211.
15. Jammousi K, Bouzguenda M, Dhieb Y, et al. Gain optimization of sliding mode speed control for DC motor. 2020 6th IEEE International Energy Conference (ENERGYCon). 2020. doi: 10.1109/energycon48941.2020.9236508
16. Shtessel Y, Edwards C, Fridman L, Levant A. Analysis of Sliding Mode Controllers in the Frequency Domain. In: Sliding Mode Control and Observation. Control Engineering. 2014. doi: 10.1007/978-0-8176-4893-0_5
17. Utkin V, Lee H. Chattering Problem in Sliding Mode Control Systems. International Workshop on Variable Structure Systems, 2006. VSS'06. 2006. pp. 346-350. doi: 10.1109/VSS.2006.1644542

18. Tahim APN, Pagano DJ, Ponce E. Nonlinear control of dc-dc bidirectional converters in stand-alone dc Microgrids. 2012 IEEE 51st IEEE Conference on Decision and Control (CDC). 2012. doi: 10.1109/cdc.2012.6426298
19. Rauf A, Li S, Madonski R, et al. Continuous dynamic sliding mode control of converter-fed DC motor system with high order mismatched disturbance compensation. Transactions of the Institute of Measurement and Control. 2020, 42(14): 2812-2821. doi: 10.1177/0142331220933415.
20. Xuan-Mung N, Nguyen NP, Pham DB, et al. Novel gain-tuning for sliding mode control of second-order mechanical systems: theory and experiments. Scientific Reports. 2023, 13(1). doi: 10.1038/s41598-023-37562-7
21. Yousef A. Experimental set up verification of servo dc motor position control based on integral sliding mode approach. JES Journal of Engineering Sciences. 2011, 39(5): 1095-1110. doi: 10.21608/jesaun.2011.129387
22. Ahmed H, Rajoriya A. Performance Assessment of Tuning Methods for PID Controller Parameter used for Position Control of DC Motor. International Journal of u- and e-Service, Science and Technology. 2014, 7(5): 139-150. doi: 10.14257/ijunesst.2014.7.5.13
23. Abdulameer A, Sulaiman M, Aras M, et al. Tuning Methods of PID Controller for DC Motor Speed Control. Indonesian Journal of Electrical Engineering and Computer Science. 2016, 3(2): 343. doi: 10.11591/ijeecs.v3.i2.pp343-349

Appendix

Parameters used for simulation of armature controlled DC motor are

$J = 5$ Kg·m^2

$f = 1$ N·m/s

$Kt = 5$ N·m/A

Sliding mode controller parameters:

$Tc = 0.198$ s