Performance Evaluation of Sliding Mode Control (SMC) for DC Motor Speed Control

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ARTICLE INFO

Article history:

Received May 28, 2023
Revised June 28, 2023
Published July 10, 2023

Keywords:

DC motor;
Speed control;
Sliding Mode Control;
PID

ABSTRACT

DC motor is an industrial motor that is practical for many applications and implementations. However, the speed of a DC motor often decreases because of the given load, thus causing it to be unstable and inconstant. In addition, parameter uncertainty is another issue of DC motors. The performance of the system will be impacted by the uncertainty. Therefore, in this study, SMC is used as speed control of the DC motor since it can handle non-linear plants. The performance also compares with PID to know the effectiveness of the SMC method in DC motor speed control. This study proposes a hardware design and implementation of DC motor angular speed control on Arduino UNO as an embedded control system. The performance comparison analysis results proved that both controllers could perform well. However, both controllers need further fine-tuning. There are still overshoot and steady-state errors for PID and SMC, respectively. In future work, the optimization method can be used to find the optimal gain or by combining it with an adaptive algorithm.

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1. INTRODUCTION

A Direct-Current (DC) motor is a device that can transform electrical power into mechanical power [1]. According to [2], DC motor has some advantages compared to AC motors, one of them is easy to control the speed or position. Numerous devices use DC motors, including stirrer systems [3], conveyors [4], mechatronics robots [5], mobile robots [6], electric vehicles [7], and industrial [8, 9]. However, the stability of its speed is challenging to control [10].

A control system for the speed of the DC motor is essential to be designed, so that the motor can rotate stably at the desired speed [11]. Generally, there are two variables in a DC motor that can be controlled: the angular position and the angular speed [12]. Several control methods have been used to control the angular speed of a DC motor such as Proportional Integral Derivative (PID) [13, 14, 15], Fuzzy Logic Controller (FLC) [16, 17, 18], and Sliding Mode Control (SMC) [19, 20].

In PID control, the parameters can be adjusted to obtain a considerably good system performance, such as good stability of its speed at the desired value and a small overshoot. Moreover, the PID controller has simplicity in its mathematical equations [21] while providing a fast system response [22], causing it to be widely used in industrial [23] and robotics applications [24]. On the other side, PID performance decreases if the plant is non-linear [15]. A fuzzy Logic Controller (FLC) is a rule-based controller. It does not need a complete system model and can be tuned based on expert experience. On the opposite side, it is not easy to be designed to find the right rule for control [25]. Meanwhile, a Sliding Mode Controller (SMC) is a high-speed switching feedback control that is effective and robust in controlling linear and non-linear systems [26]. According to [27], it can handle plant non-linearity, and time-varying system and has good ability over a wide range.

Parameter uncertainty is another issue of DC motors [28]. DC motors' resistance and inductance are susceptible to changes as a result of temperature changes. In addition, it may happen as a result of prolonged use, advanced age, and outside disturbances. The performance of the system will be impacted by the uncertainty. Therefore, in order to make the system function works properly, the controller must be robust to uncertainty. In this study, SMC is used as speed control of the DC motor. The study aims to evaluate the effectiveness of SMC as a speed control method for DC motors, specifically in comparison to PID control.

The sequence of this article is organized as follows. Section 2 discusses the material and method used in this study. The results and discussion are presented in Section 3. The last section is the conclusion, which will summarize the findings and suggestion for the future directions.

2. METHODS

This study presents a prototype design, including the hardware design and implementation of the angular speed control in a DC motor using SMC and PID based on Arduino UNO as the embedded controller. Other tools used in the study were the L298N Motor Driver and JGA 25- DC Motor 370 (including the encoder).

2.1. System Design

As the main component in the research, a control method (PID/SMC) that had been applied to a microcontroller, Arduino UNO, was given to a DC motor so that the angular speed of the DC motor followed the referenced value. As the augmented system's main controller, the Arduino UNO was connected to the DC motor through a motor driver. The Arduino UNO contained the source code of the PID/SMC control method that calculated the control signal based on the output of the DC motor measured by the encoder. Then, the controller's output or the control signal was processed by the motor driver before being delivered to the DC motor as the input voltage. The augmented system was powered with 12V DC through the DC jack adaptor of the Arduino UNO and the 12 Volt power adaptor, as shown in Fig. 1.

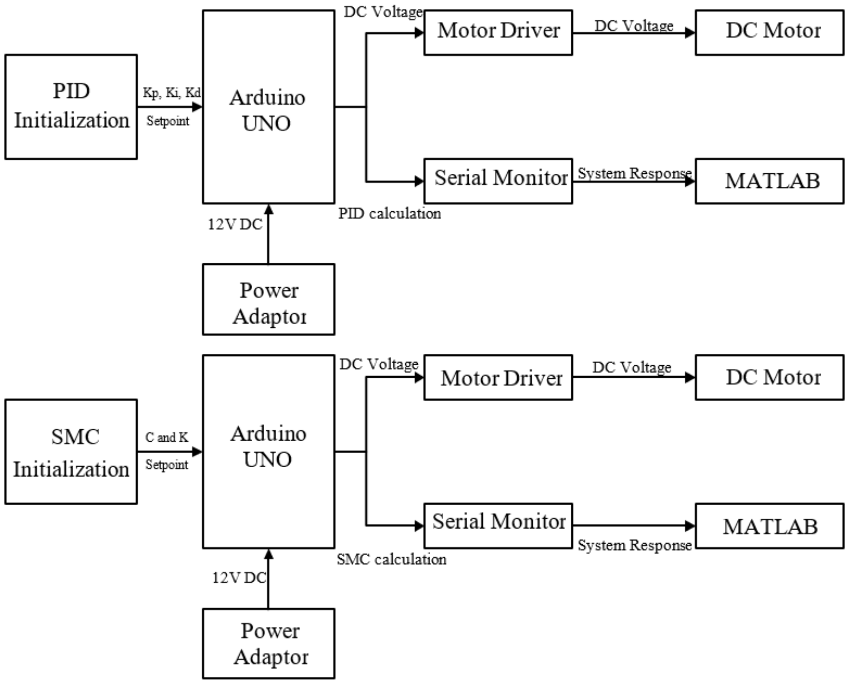

Fig. 1. Block Diagram of PID and SMC

Fig. 1 is the block diagram of the angular speed control system in a DC motor using PID and SMC. The overall system can be described as follows. Initialization of the controller was done by defining the values of each controller's parameters and the desired angular speed of the DC motor or setpoint in the Arduino IDE platform. In the PID controller, the controller's parameters to be defined in the initialization were the controller gains: proportional (Kp), integral (Ki), and derivative (Kd). Meanwhile, SMC gain values (c and K) were defined in the initialization of SMC. As the controller's output, the control signal was given to the DC motor by the motor driver, which delivered it as the input voltage to the DC motor. At the same time, the calculation resulted in PID/SMC controllers were also sent to the serial monitor. The angular speed of the DC motor depends on the amount of the input voltage; a bigger input voltage means a faster motor rotation and vice versa. Aside from the PID/SMC calculations, the output of the DC motor in a specified time interval was also sent to the serial monitor. The measured output was processed by MATLAB, along with the calculations from the control method. MATLAB then plotted the results graphically and displayed the result.

The hardware design of the prototype began with making a wiring diagram of the components and then followed by assembling the components. Assembling the components means connecting and wiring all electrical components until the system can run properly. Fig. 2 is the designated wiring circuit diagram of the system. All components were connected to the Arduino UNO with power supplied from the 12V power adaptor. The motor driver and the DC motor were connected directly to Arduino pins. The list of Arduino pins that were used in the wiring diagram can be seen in Table 1.

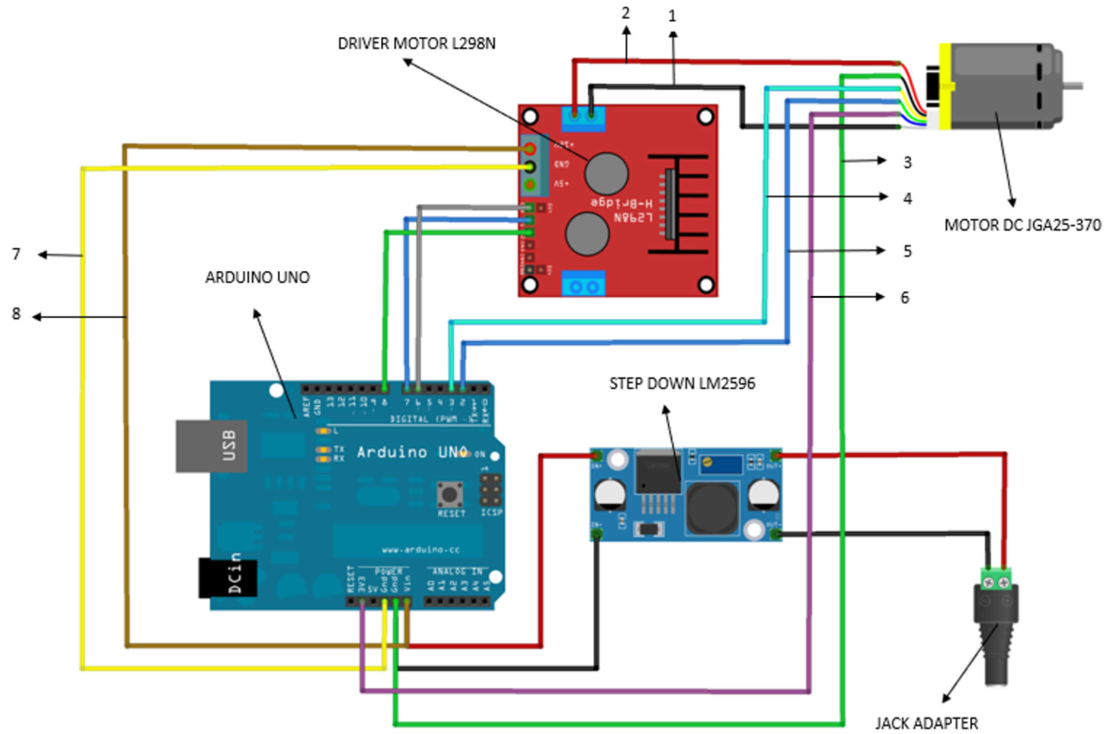

Fig. 2. Wiring diagram of the hardware system

Table 1. Arduino I/O pins

No	Arduino Pin	Description
1	Driver Motor (-)	Driver Motor (-) to Motor
2	Driver Motor (+)	Driver Motor (+) to Motor
3	GND	GND Arduino to GND Encoder Supply (-)
4	D3	Connected to Encoder Chanel A and DC motor
5	D2	Connected to Encoder Chanel B and DC motor
6	3.3	VCC 3.3 Volt and Encoder Supply (+)
7	Gnd	Ground Driver Motor & Ground Encoder
8	Vin	VCC 12 Volt Driver Motor

The prototype design also included the mechanical cover and placement of the components in a 3D design. The size of each component was estimated to build the mechanical cover. The mechanical cover of the prototype was made of plastic, and the DC motor would be placed later on the top of the box. The Arduino UNO and the driver motor were placed inside the plastic box. There were holes on the top of the box to place the banana jacks, so that the prototype could be used as a knockdown system. Hence, this prototype can also serve educational purposes due to its knockdown characteristics; users can easily understand and use it. The 3D design and system prototype are presented in Fig. 3. A detailed explanation regarding the design of the prototype along with its components, can be seen in Table 2.

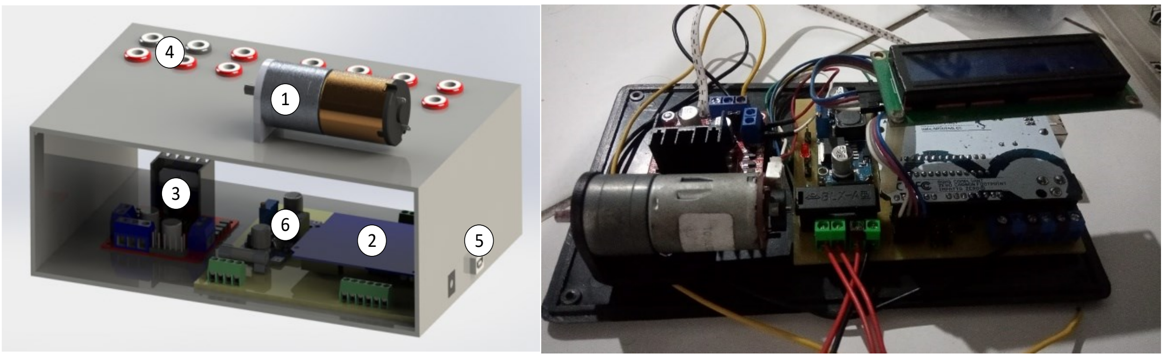

Fig. 3. 3D system design and system prototype

Table 2. A detailed list of the components

No	Components	Descriptions
1	DC Motor (JGA-25 370)	Main controlled component
2	Arduino UNO (ATmega 328)	The main controller of the augmented system
3	Motor Driver (L298N)	As a bridge that connects the Arduino and the DC motor
4	Banana Jack	A socket or plug between connecting cables and the mechanical cover
5	Jack Adaptor	A power supply from the 12V power adaptor
6	Step Down (LM2596)	To reduce or limit the voltage from the 12V power supply to the 5V Arduino UNO

2.2. Control Methods

The connection between the control method and the hardware system can be illustrated in Fig. 4. The block of SP and control method is a software system coded inside the Arduino. Whereas the others are a physical system. Both PID and SMC are a feedback control with angular speed as a feedback signal.

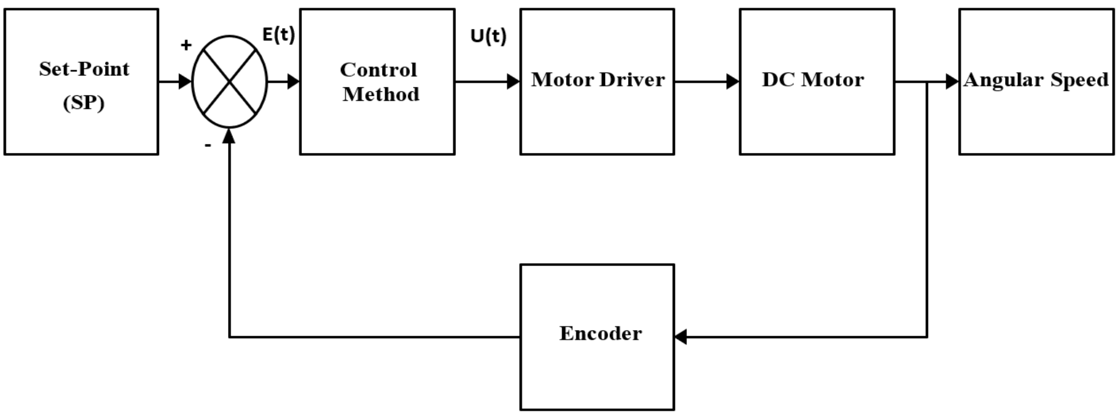

Fig. 4. Controller block diagram

SMC first appeared when researchers were looking for solutions to oscillation problems in bang-bang control [29]. In this control method, all state variables are enforced to reach the sliding surface, following the surface line toward the equilibrium point. The main part of SMC is to design the sliding surface and manipulate the state variables' input. Meanwhile, the main control objective of SMC is to make the system response follow the desired trajectory, known as the sliding surface. It can be done by comparing the actual state (x) with the desired state (xd). In sliding surface, a disturbance is denoted as a function and defined as the distance between the measured signal to the sliding surface, denoted as $s = x - xd$. A condition when the system achieves the sliding surface is called sliding mode, in which $s = 0$.

The SMC's control signal is split into two components: the reaching mode and the sliding mode. Reaching mode calls for switching control (u_{sw}) to bring the system's state to a sliding surface. Additionally, an equivalent control (u_{eq}) is present in the sliding mode state to maintain the state system's stability. Equation (1) can be used to represent the sliding mode control signal, while Equation (2) represents switching mode control. The SMC diagram for a control signal that comprises switching control and equivalent control is shown in Fig. 5.

$$u_{SMC}(t) = u_{eq} + u_{sw} \tag{1}$$

$$u_{sw} = K\frac{s}{|s| + \delta} \tag{2}$$

$$s = ce + \dot{e}$$

In which $K > 0$ is selected sufficiently large. The higher value of K, the faster trajectory converges to the sliding surface. Whereas, δ is a small tuning scalar called a tuning parameter to reduce chattering. Then, s is sliding function and c is sliding mode control constant.

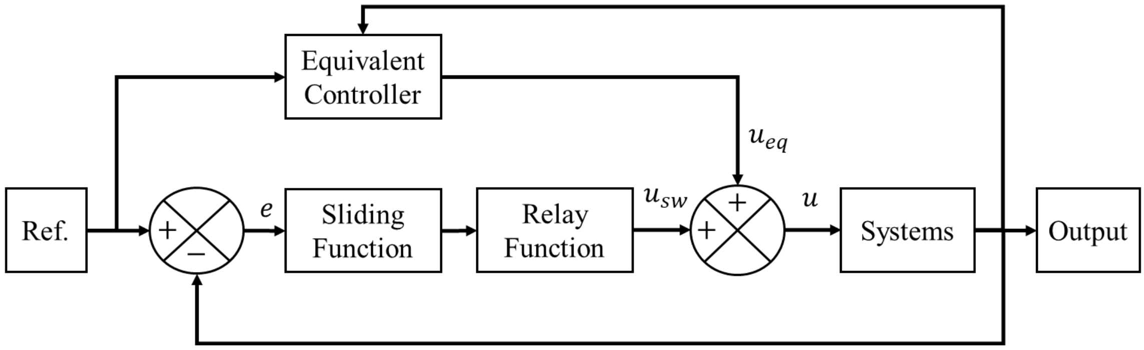

Fig. 5. Diagram block of Sliding Mode Control (SMC) [30]

PID (Proportional–Integral–Derivative) is a feedback controller that is commonly used in industrial control systems. It continuously calculates the error as the difference between the desired setpoint and the measured output variable. Then, the controller attempts to minimize the error at that time by adjusting the control variable. Such control variables can be manifested as the position of the control valves, the damper, or the power in the heating elements. Based on several reviews and analyses of the advantages and drawbacks of each control mechanism, a parallel combination was built between the three control mechanisms. Each control mechanism has different influences on system performance. For instance, it can make the system respond in a fast system response, eliminate an offset, or generate a big rising time. PID controller also utilizes a closed-loop control mechanism, in which the control signal is proportional to the difference between the measured output variable and the desired output value. The feedback mechanism in the control method is to obtain the difference of the measured output variable. A parallel combination of the proportional, integral, and derivative control can be expressed mathematically as

$$u(t) = Kp\, e(t) + Ki \int e(t)\, dt + Kd\frac{de(t)}{dt} \tag{3}$$

In which $u(t)$ is Control signal, $e(t)$ is Error signal, Kp is Proportional gain constant, Ki is Integral gain constant and Kd is Derivative gain constant

The design of the software was to program the Arduino UNO microcontroller through the Arduino IDE platform. The source code was then downloaded to the board using the USB connection port. The flowchart of the source code can be seen in Fig. 6 which angular speed control system of the DC motor was built based on PID and SMC controller. According to the flowchart, the system would continuously update and measure the output variable, which was the angular speed of the DC motor, until the error or the difference between the desired value and the measured output was equal to zero.

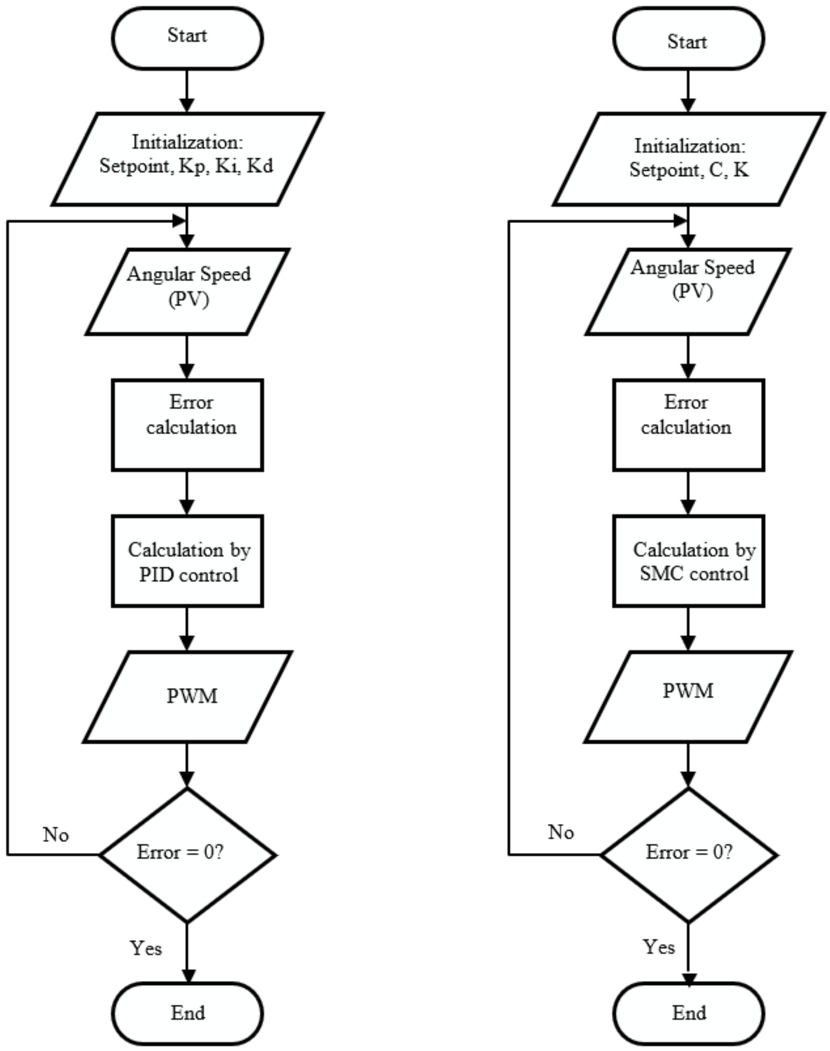

Fig. 6. Control algorithm flow

3. RESULTS AND DISCUSSION

The overall system was evaluated by analyzing the system's performance when given varying controller parameters. In the augmented system using the PID controller, the analysis and evaluation of the system were conducted based on the system's performance with varying Kp, Ki, and Kd. Meanwhile, the analysis and evaluation of the augmented system using the SMC controller were done based on the system's performance with different c and K values, in which c is the gain in the equivalent control. Then, the results of both controllers were compared in the performance comparison analysis. The system simulation was repeated four times for each controller with different values of the controller's parameters. The results of the simulation and the discussions are provided in the following subsections.

3.1. PID Evaluation

The simulation results using different Kp, Ki, and Kd values are presented in Fig. 7. According to the figure, all system responses showed insignificant overshoot, and the output was stable at the given reference value. Moreover, due to insignificant changes in Kp, Ki, and Kd values, all system responses were almost identical in shape. However, it can be seen that there was a slight difference during the transition time.

Table 3 presents detailed system performance information with different Kp, Ki, and Kd values. The best result was obtained from the second test, which used $Kp = 0.1$, $Ki = 0.09$, and $Kd = 0.04$ as the controller's parameters, resulting in a fast-rising and settling time while having insignificant overshoot. Overall, in this test, the PID responses have overshoot and error. Further, it needs to evaluate PID gain.

Table 3. System performance with PID control

Kp	Ki	Kd	Rise time (Tr)	Overshoot (Mp)	Peak time (Ts)	Settling time (Ts)	Error
0.1	0.08	0.02	3.3953	1.1429	20	9.3333	-2
0.1	0.09	0.04	2.9619	1.1429	18	6.7778	-2
0.1	0.08	0.07	4.2917	1.1429	31	9.6667	-2
0.12	0.08	0.07	4.4689	1.1429	38	11.1667	-2

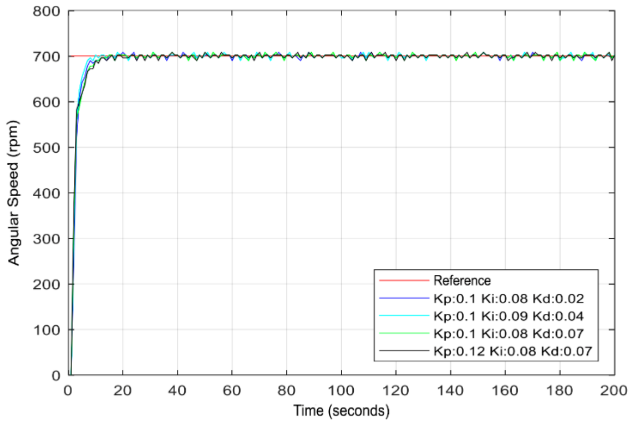

Fig. 7. PID performance

3.2. SMC Evaluation

The simulation results using different c and K values are presented in Fig. 8. The first three simulations were almost identical in shape, with no overshoot in the observation. However, the final output value could not reach the reference value (700 rpm), causing the system to have a steady-state error. In contrast, the result from the fourth simulation using $c = 10$ and $K = 135$ had oscillations when the system's output almost reached the setpoint. This is due to the higher value of K.

Table 4 presents detailed system performance information with different c and K values. It can be seen that the system could not reach the desired angular speed. Overall, from the four tests, it can be resumed that the performance of SMC in this test has a steady-state error. The gain value needs for fine-tuning to improve the performance.

Table 4. System performance with SMC control

c	K	Rise time (Tr)	Overshoot (Mp)	Peak time (Ts)	Settling time (Ts)	Error
10	133.9	3.2966	0	13	87.3333	4
10	134	3.2354	0	13	87.1667	4
10	134.9	3.3029	0	13	87.1667	4
10	135	3.1752	0.2857	59	99.1667	4

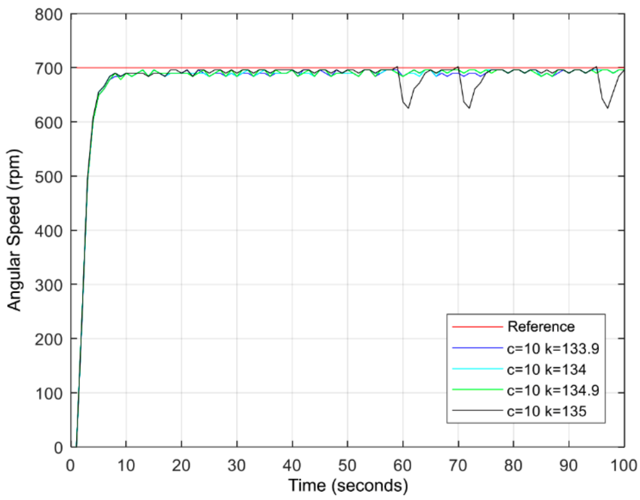

Fig. 8. SMC performance

4. CONCLUSION

The angular speed control system of a DC motor was successfully built and designed based on PID and SMC controller. By using the trial-and-error method, the best PID parameter obtained in the study was the combination of $Kp = 0.1$, $Ki = 0.09$, and $Kd = 0.04$. Meanwhile, the best c and K values of the SMC obtained from the trial-and-error were $c = 10$ and $K = 134$. The performance comparison analysis results proved that both controllers could perform well. However, both controllers need further fine-tuning. There are still overshoot and steady-state errors for PID and SMC, respectively. For future improvement, the optimization method can be used to find the optimal gain or by combining it with an adaptive algorithm.

Acknowledgments

The authors would like to express gratitude to the honorable editor and reviewers for their suggestions and supporting remarks so that the paper can be published. Also, thank you to Peneliti Teknologi Teknik Indonesia for funding and research grant.

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