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Position control of a DC servo motor using various controllers: A comparative study

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ABSTRACT

In contrast to Direct Current (DC) motors, the angular position of a DC servo motor (DSM) can be regulated at a specific angle using a control signal. Due to its high power rating and speed, DSM is frequently preferred. The aim of the study is to compare the time domain characteristics of system response using proportional (P), proportional-integral (PI), proportional-integral-derivative (PID) controller, state-feedback controller (SFC), and SFC with Integral Action (SFCIA). The DSM is a 3rd order system, and the study differentiates different types of controllers for position control of the DSM in MATLAB. The P, PI, and PID controllers are designed by the Ziegler and Nichols (ZN) method. The SFC is designed by determining the state feedback gain matrix using Ackermann's formula. However, the SFCIA is designed by placing the poles and adding an integrator to the DSM. According to the simulation results, SFCIA has the best performance in terms of peak overshoot (M_p) and settling time (t_s) as compared to other controllers (P, PI, PID, and SFC). The proposed method could be applied to the higher-order systems also.

1. Introduction

The electrical servo motor is vital in the present diligence. Servo motors are utilised in an assortment of applications in modern gadgets and advanced mechanics that incorporate precision positioning as well as speed control. Servomotors use a feedback controller to control the speed or position of the motor, or both. With the exception of constructional highlights, a DC servo motor (DSM) is basically a normal DC motor [1,2]. The actual prerequisites of DSM are low inertia and high starting torque. Low inertia is accomplished with diminished armature width resulting in increased armature length to such an extent that the ideal power output is reached [3].

The essential persistent feedback controller is the Proportional-Integral-Derivative (PID) controller, which has great execution. Anyway, it is versatile enough just with adaptable tuning. Despite the fact that many advanced control procedures have been proposed to improve system exhibits, such as self-tuning control, model reference versatile control, sliding mode control, and fuzzy control, the ordinary Proportional Integral (PI)/PID controllers are still prevailing in the majority of verifiable servo systems [4,5]. The proportional gain K_p, the integral gain K_i, and the derivative gain K_d should all be carefully resolved before implementing a PID controller. A variety of PID controller bounds for single-input-single-output (SISO) systems have been determined using a variety of approaches [6,7]. PID controllers are as yet not implemented in industry. There have been a variety of ways to deal with searching the boundaries of PID controllers, including time reaction tuning, time space optimization, frequency domain shaping, and genetic algorithms. However, the majority of them necessitate extensive experience and numerous iterations. Since linding the best possible boundaries of PID controllers is certainly not a simple task, it is critical to develop an essential methodology [8].

Because of its phenomenal speed control attributes, the DSM has been generally utilised in industry despite the fact that its support costs are higher. Therefore, position control of DSM has drawn significant exploration, and a few strategies have developed. For DSM speed and position control, proportional (P), PI, and PID controllers have been widely used [9]. The State-Feedback Controller (SFC) is meant to solve the problem that P, PI, and PID controllers have in achieving desired responses. The value of the feedback gain matrix is calculated using Ackermann's formula. Then, to generate the desired time domain response, state-feedback with integral

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action (SFCIA) is used [10,11]. In earlier studies, position control of DSM was controlled by various controllers rather than P, PI, PID, and SFCIA. Dipraj et al. (2021) [12] investigated the use of a traditional PI controller and a fuzzy logic controller to control the speed of DSM. The traditional tool, MATLAB/Simulink, is used to examine the model exactly so that the servo motor's performance is suitable. Pillai and Nair (2017) [13] created a PID controller and a Model Reference Fuzzy Adaptive Controller in LabVIEW for DSM position control and compared their performances, with the Fuzzy controller providing consistent output with minimum overshoot. Szczepanski et al. (2020) [14] explain an application of a nature-inspired optimization algorithm to the automatic tuning of a state feedback speed controller (SFC) for two-mass systems (TMS) is proposed. In order to obtain optimal coefficients of SFC, the Artificial Bee Colony algorithm (ABC) is used. Mezher (2021) [15] used LabVIEW to create speed control for a servo DC motor using a PID controller with different tuning options. With Simulink MATLAB simulation and Arduino hardware implementation, Maarif and Setiawan (2021) [16] suggested an integrated state feedback method for tracking control in DC motors. Salman et al. (2021) [10] explain the evaluation of the speed control of a DC motor utilising a state-feedback controller for stability and performance analysis.

Thus, assuming the mathematical model of the plant (DSM), it is feasible to apply different strategies for deciding the boundaries of the controller that can gather the transient and steady-state requirements of the closed-loop system. The DSM is used in this work to obtain the transfer function between shaft position and armature voltage. SFC is developed to defeat the difficulty faced in accomplishing desired response by the PID controller. The value of the feedback gain matrix is calculated using Ackermann's formula. Subsequently state-feedback with integral action is applied to achieve desired time domain response. The unit step response is used to assess each controller operation. As a result, the goal of this research is to develop P, PI, PID, SFC, and SFCIA controllers for controlling the position of the DSM and evaluate their performance using the MATLAB simulation tool.

2. Modeling of DSM

A DSM is used in a control system to provide a measurable measure of shaft power. The DSM is either field-controlled with a fixed armature current or armature-controlled with a fixed field. A fixed permanent-magnet field is applied by DSM in the apparatus, and the control signal is applied to the armature terminals. Fig. 1 depicts the electrical model of such a DSM. The armature voltage, V, is the voltage used to regulate the motor by an amplifier. R, L, and K are the resistance, inductance, and back-emf constants of the DSM. The back emf, e, is caused by the armature windings rotating in a fixed magnetic field [2].

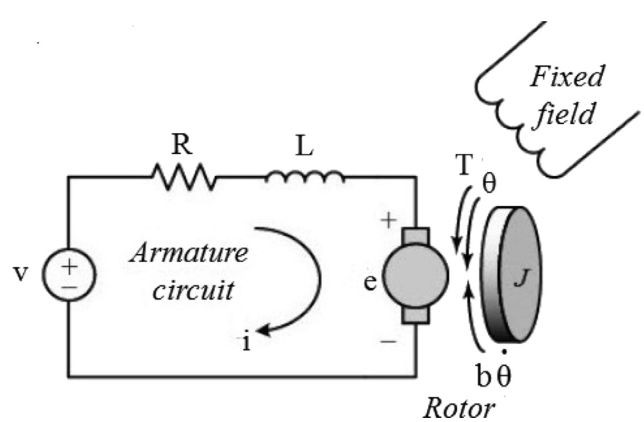

Fig. 1. Schematic representation of the DSM.

Apply KVL to armature circuit,

$$V = L\frac{di}{dt} + Ri + e \tag{1}$$

The torque equation is,

$$T = J\ddot{\theta} + b\dot{\theta} \tag{2}$$

The motor torque, T, is proportional to the armature current, i,

$$T = K_t.\ i \tag{3}$$

The back emf, e, is proportional to the rotational velocity,

$$e = K_e\dot{\theta} \tag{4}$$

After simplification the transfer function of the DSM is given in Eq. (1),

$$\frac{\theta(s)}{V(s)} = \frac{K}{s[(Ls+R)(Js+b)+K^2]} \tag{5}$$

The different parameters of the DSM are given in Table 1 [17]. Thus, the overall transfer function of the DSM is given below:

$$\frac{\theta(s)}{V(s)} = \frac{1.2}{0.00077s^3 + 0.0539s^2 + 1.441s} \tag{6}$$

3. Controllers

3.1. P controller

The P-control behavior is mathematically illustrated in Eq. (7) [5],.

$$c(t) = K_c e(t) + b \tag{7}$$

where: c(t) = controller output, K_c = controller gain, e(t) = error, b = bias.

3.2. PI controller

The controller output is linked to the error and the integral of the error in PI control. The mathematical representation of this PI-control behaviour is given in Eq (8) [5,8], where: T_i is the integral time and C is the initial value of the controller.

$$c(t) = K_c\left(e(t) + \frac{1}{T_i}\int e(t)dt\right) + C \tag{8}$$

3.3. PID controller

All three types of control mechanisms are combined in PID control. This control is most widely employed as it incorporates the benefits of each type of control.

The controller output is correlated to the error, integral of the error, and derivative of the error in PID control. Eq. (1) shows the mathematical representation of this PID control behaviour (9)

Table 1
Considered parameters of the DSM.

Parameters	Values
Armature resistance (R)	2.45 Ω
Armature inductance (L)	0.035H
Torque constant (K_t = K)	1.2 N-m/A
Electromotive force constant (K_e = K)	1.2 V/(rad/sec)
Moment of inertia (J)	0.022 Kg-m^2/rad
Damping coefficient (b)	0.0005 N-m/(rad/sec)

[5,8], where: T_i = integral time, T_d = derivative time constant, C = initial value of the controller.

$$c(t) = K_c\left(e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de}{dt}\right) + C \quad (9)$$

3.3.1. Conventional approach

For tuning P, PI, and PID controllers, as well as finding the values of proportional gain K_p, integral time T_i, and derivative time T_d, the second approach of Ziegler-Nichols (ZN) rules is used. Table 2 shows how to calculate the ZN setting value using the formula (where: K_{cr} is critical gain and P_{cr} is the period of oscillation). The gain values of several controllers (P, PI, and PID) after simulation are represented in Table 3 [18]. However, Fig. 2(A), 2(B), and 2 (C) show the step response of the DSM with a typically tuned P, PI, and PID controller using the above algorithm.

3.4. State-Feedback controller

The full-state variable feedback control approach refers to the concept of feeding back all of the state variables to the system's input through a proper feedback matrix in the control strategy. The desired placement of the closed-loop poles of the system will be specified using this method. The goal is to create a feedback controller that moves part or all of the measured system's open-loop poles to the given closed-loop pole location. As a result, this method is sometimes referred to as "pole-placement control design", as shown in Fig. 3 [10].

The following is the general version of the state equation:.

Table 2
Control rule setting.

Controller	K_p	T_i	T_d
P	0.5 K_{cr}	∞	0
PI	0.45 K_{cr}	P_{cr}/1.2	0
PID	0.6 K_{cr}	P_{cr}/2	P_{cr}/8

Table 3
Gain values of P, PI and PID controllers.

Controller	K_p	K_i	K_d
P	42.04	0	0
PI	37.83	312.64	0
PID	50.44	695.7	0.92

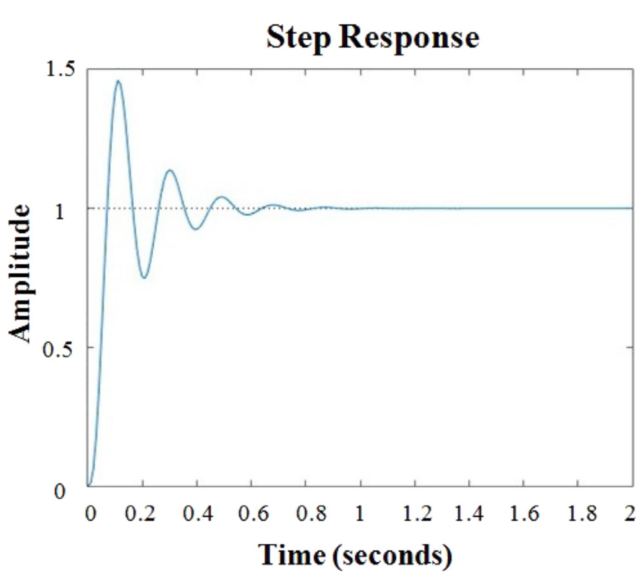

Fig. 2. (A). Step response of the DSM with conventionally tuned P controller. (B). Step response of the DSM with conventionally tuned PI controller. (C). Step response of the DSM with conventionally tuned PID controller.

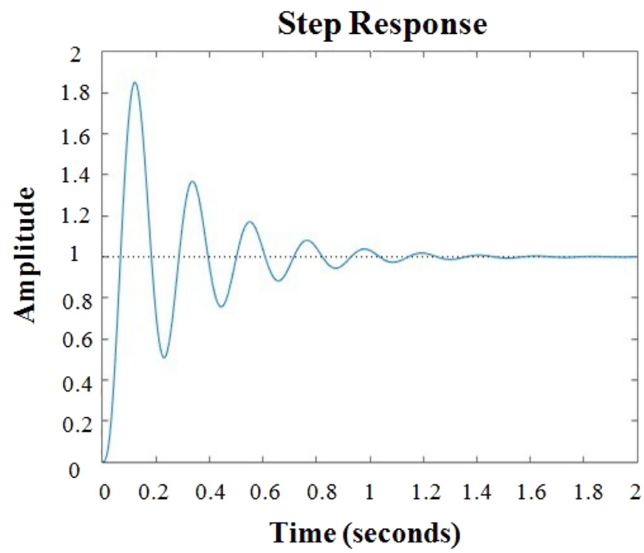

Fig. 2 (*continued*)

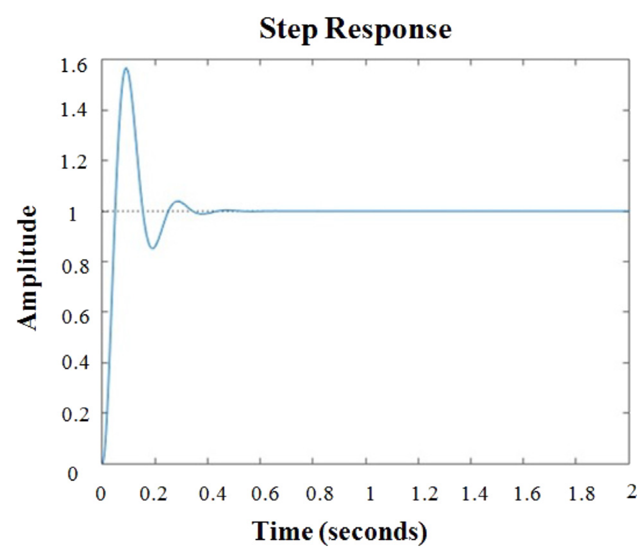

Fig. 2 (*continued*)

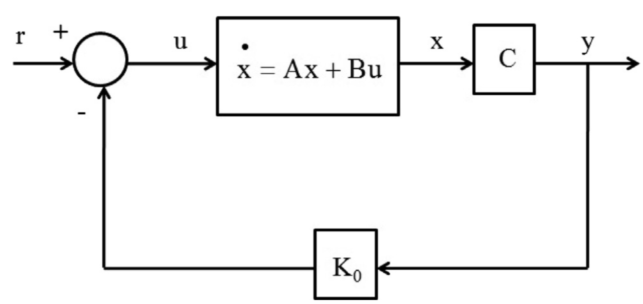

Fig. 3. Pole-placement control design.

$$\dot{X} = Ax + Bu \quad y = Cx \tag{10}$$

Normally, designing the state feedback controller by using only the pole-placement design will have one major disadvantage: a large steady-state error will be introduced. In order to compensate for this problem, an integral control is added where it will eliminate the steady-state error in responding to a step input [10,11]. The state space formulation of DSM has been derived in this study, and the following matrices have been obtained:.

$$A = \text{system matrix} = \begin{bmatrix} 0\ 1\ 0 \\ 0\ \text{-}\ 0.023\ 54.54 \\ 0\ \text{-}\ 34.28\ \text{-}\ 70 \end{bmatrix}$$

$$B = \text{control matrix} = \begin{bmatrix} 0 \\ 0 \\ 28.57 \end{bmatrix}$$

$$C = \text{output matrix} = [1\ 0\ 0]$$

The state-space equations that result after adding the K_0 matrix to the system are given below:.

$$\dot{x} = (A - BK_0)x + Bu \quad y = Cx \tag{11}$$

The closed-loop poles can be positioned at desirable positions by developing a full-state feedback controller. The feedback gain matrix is generated using Ackerman's formula with the poles at "-18.1 ± 13.58i" as follows, and Fig. 4 depicts the full SFC output response.

$$K_0 = [9.96\ \ -0.17\ 0.11]$$

3.5. State-Feedback controller with integral action

The controller will now use the integral of the output as feedback to eliminate steady-state error. By reconfiguring the controller, one closed-loop pole for each pole in the DSM is required. Hence, another pole at -30.38 is added, which will be quicker than the other poles. The output response of full state feedback with integral control is depicted in Fig. 5 from these poles.

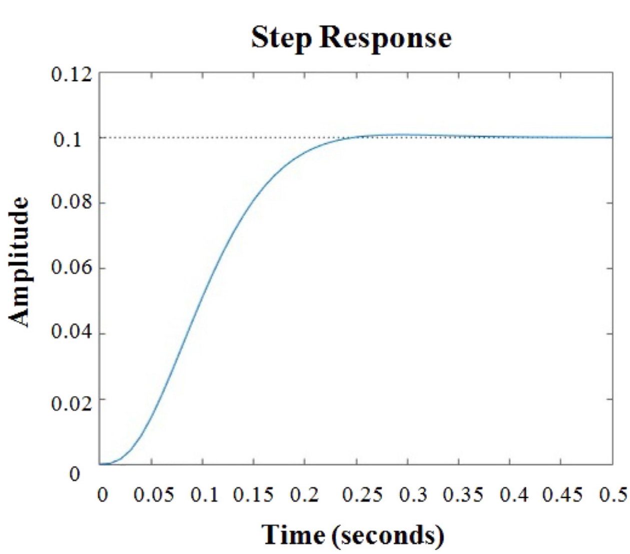

Fig. 4. Step response of the DSM with Full SFC.

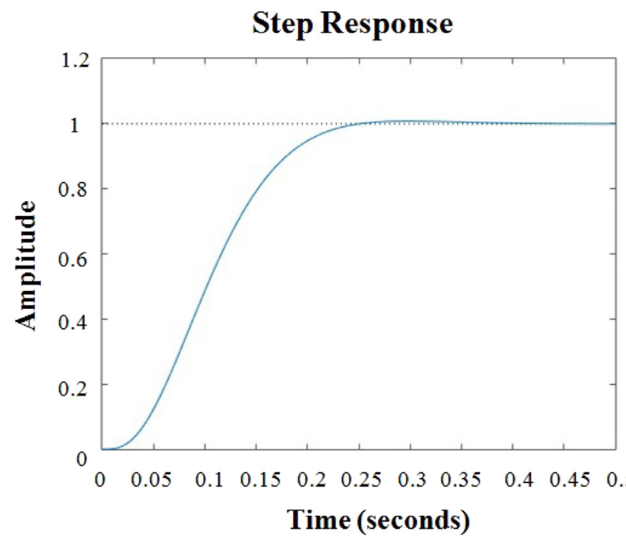

Fig. 5. Step response of the DSM with Full SFCIA.

Table 4
Analysis of controllers.

Type of Controller	Maximum overshoot (Mp) (%)	Steady-state error (ess)	Settling time (ts) (sec)
P	49	zero	0.9
PI	85	zero	1.6
PID	57	zero	0.43
SFC	−90	zero	0.25
SFCIA	1	zero	0.25

4. Results and discussion

The implementation of commonly tuned controllers (P, PI, and PID) does not yield accurate results. The results from the P, PI, and PID controllers reflect the underdamped response (position) of the DSM. But the application of SFCIA yields better time specification performance. Table 4 displays the outcomes of the MATLAB simulation. All the controller's results have zero steady-state error. The result of the SFC and SFCIA represents a critically damped response of the system. Also, the settling time is same for both SFC and SFCIA. However, SFC results in a negative overshoot response from the system. When the results are compared, it can be shown that the developed SFCIA has a considerably faster response than the other controllers (P, PI, PID, and SFC) in terms of maximum overshoot and settling time.

5. Conclusion

In this paper, a mathematical model of DSM is developed. The P, PI, and PID controllers are presented and applied to the DSM using the ZN technique and SFC with and without integral action have been developed using pole-placement technique. The controller's performance criteria are defined in the time domain. The step response is used to examine and compare the controller's performance in MATLAB. The designed controllers have been simulated and observed to have good performance. The comparison of position control of the DSM by various controllers clearly reveals that the SFCIA performs better than the other controllers.

CRediT authorship contribution statement

Debika Debnath: Conceptualization, Methodology, Investigation, Supervision, Writing – review & editing. **Piyali Malla:** Data curation, Software, Validation, Writing – original draft. **Sanchita Roy:** Data curation, Software, Validation, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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