DC Motor Angular Speed Stability Study Using The Fuzzy PID Controller

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Abstract: In the realm of automated control, the reason DC motors are so popular is their inexpensive cost and small number of components. The control system's parameters determine the DC motor's stability and control precision. The PID control is a well-established method used in many industrial fields. But in some cases, the PID control couldn't make excellent control of the DC motor due to the DC motor's non-linearity. The fuzzy PID controller provides an efficient way to optimize the traditional PID controller. In this paper, two closed loops of conventional PID control and the fuzzy PID control are built in Matlab Simulink. The original PID parameters are obtained by using the trial-and-error method, and the adaptive modified PID parameters are obtained by fuzzy rules. Additionally, the membership functions of the fuzzy inputs and outputs are the Triangle membership function and the Gaussian membership function. The two systems' step response graphs are contrasted with one another. Their rise time, transient time, peak time, settling time, and overshoot are analyzed. According to the simulated results, the fuzzy PID controller performs more steadily and with a quicker response than the traditional PID controller.

Keywords: PID control, DC motor, Fuzzy algorithm, Matlab Simulink

1 Introduction

The two parts that constitute a DC motor are its moving and stationary portions. The stator is the part of a DC motor that remains stationary while operating. The stator's primary function is to generate a magnetic field. The rotor, which is the component that rotates during an activity, is primarily responsible for producing electromagnetic torque and electromotive force [1]. After being widely used in industrial applications for a significant period, such as industrial machinery, automotive industry, and robotics industry, the DC motor has gained popularity due to its numerous benefits: high efficiency, excellent speed control, compact size, etc. Therefore, it is of vital importance to study the angular speed control of the DC motor [2].

Without a controller, the DC motor is unable to achieve great dynamics and consistent performances for a certain working aim. One such technology that is becoming more and more important for particular applications is the automatic control system. According to reports, conventional PID (Proportional-Integral-

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Derivative) controllers make up more than 90% of controllers used in industrial process control applications because they are the most straightforward, easily applied, and simple-to-use controllers available. However, the DC motor is a non-linear dynamical system that is more challenging to construct, and even once it is, it frequently varies in an unforeseen way. Especially when the setting point range is greater, which frequently leads to overshoot and impaired control performances [3-5].

The fuzzy control system is a type of control system that uses fuzzy logic to mimic human decision-making. Fuzzification, fuzzy inference, and defuzzification are the three primary parts of fuzzy control systems. Compared to the traditional PID controller, the fuzzy controller has three advantages: First of all, since fuzzy control systems don't rely on linear mathematical models, they are more appropriate for nonlinear systems. Whereas conventional PID controllers would have trouble, they can successfully regulate systems with intricate and nonlinear dynamics [6]. Secondly, systems using fuzzy control are naturally resistant to ambiguity and imprecision. They are suitable for systems with uncertain or changeable characteristics because they can manage ambiguous and unclear information by utilizing fuzzy sets and linguistic variables [7]. Thirdly, fuzzy control systems are inherently adaptive, they can modify their behavior in response to changes in the environment or the system itself. They could be used in systems with different specifications or operating circumstances because of their flexibility [8].

In this paper, a fuzzy PID controller and a conventional PID controller are adopted to control the DC motor. The transfer function of the DC motor is carried out as the plant which is also called a controlled object. To compare the motor speed performances under two types of controllers, two closed-loop control systems are built to observe the motor's performances. The control parameters are obtained by the trial-and-error method. These parameters will be used as the original settings of the fuzzy PID controller. The optimal PID parameters in fuzzy PID are combined with the original parameters and the outputs of the fuzzy controller.

2 Mathematical Model of DC Motor

It is important to pay attention to two important characteristics to determine the DC motor's transfer function: The voltage applied to the motor at the input and the angular velocity at the output. Fig. 1 displays the equivalent circuit of a DC motor.

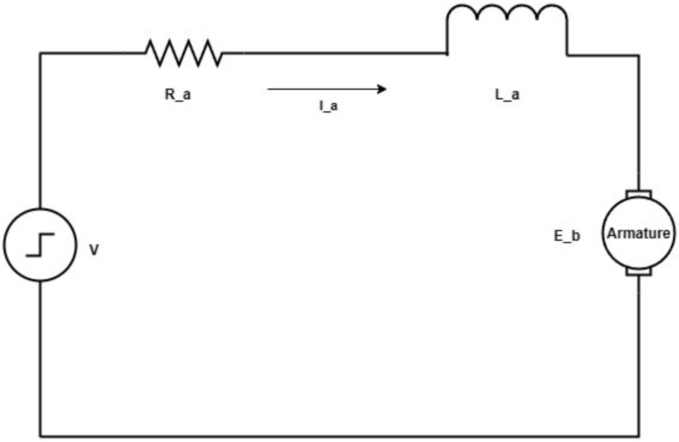

Fig. 1. Equivalent circuit of DC motor (Photo credited: Original)

Usually, the following parameters are needed to calculate the equations for electrical and mechanical dynamics.

R_a: Armature resistance
L_a: Armature inductance
E_b: Back electromotive force (EMF)
V: Voltage source
I_a: Armature current
T_m: Torque generated by the motor
T_{load}: Torque of the load
J: Moment of inertia
B : Viscous friction coefficient of motor
ω : Angular velocity of motor
K_t: Torque constant of motor
K_b: Back EMF constant

2.1 Equations for Electrical and Mechanical Dynamics

Electrical Equations

The voltage equation for the motor, is:

$$V = E_b + I_a R_a + L_a \frac{dI_a}{dt} \quad (1)$$

Where E_b is proportional to the angular velocity ω:

$$E_b = K_b \omega \quad (2)$$

Mechanical Equations

The motor torque (T_m) is proportional to the armature current (I_a):

$$T_m = K_t I_a \quad (3)$$

The system mechanical dynamics could be written by:

$$T_m - T_{load} = J\frac{d\omega}{dt} + B\omega \quad (4)$$

DC Motor's Transfer Function

To carry out the transfer function $\frac{\omega(s)}{V(s)}$, where $\omega(s)$ and $V(s)$ are the Laplace transforms of $\omega(t)$ and $V(t)$ respectively. Table 1 indicates the implementation parameters of the DC motor.

Table 1. Parameters of DC Motor [9]

Parameters	Value
Armature inductance (H)	L = 0.1215H
Armature resistance (ohm)	R = 11. 2 Ω
Moment of inertia (kg·m^2)	J =0.02215 kg·m^2
Viscous friction coefficient (N·s/m^2)	B = 0.002953 N·s/m^2
Motor torque constant (N·m/A)	K_t =1.28 N·m/A
Back emf constant (V·s/rad)	K_B =1.28 V·s/rad

The transfer function of the DC motor could be written by:

$$\frac{\omega(s)}{V(s)} = \frac{K_t}{(sL_a+R_a)(sJ+B)+K_tK_B} \quad (5)$$

So,

$$\frac{\omega(s)}{V(s)} = \frac{1.28}{0.0027s^2+0.2481s+1.671} \quad (6)$$

3 Models Design of PID Controller

3.1 Conventional PID Controller

Conventional PID controller has been a widespread tool employed in plenty of areas due to its simplicity, robustness, and tuning flexibility. In general, P, I, and D respectively correspond to Proportional term, Integral term, and Derivative term. The derivative, integral, and proportional terms add up to the control signal u(t) produced by the PID controller:

$$u(t) = K_p \cdot e(t) + K_i \cdot \int e(t)dt + K_d \cdot \frac{de(t)}{dt} \quad (7)$$

Where the control signal given to the system is denoted by $u(t)$. The error signal, denoted as $e(t)$, is defined as the difference between the process variable and the reference signal. K_p, K_i, and K_d are the proportional, integral, and derivative gains respectively.

The current error signal is the difference between the anticipated setpoint and the actual process variable. The output of the proportional term is proportionate to this difference. In addition to offering rapid response to system changes, the proportionate action helps to lower the steady-state inaccuracy. The output of the integral term, which integrates the error signal across time, is proportional to the total cumulative error signal. By continuously modifying the control signal to push the system in the direction of the setpoint, it works to remove the steady-state error. In addition to ensuring that the steady-state error is reduced or eliminated, the system's capacity to react to disturbances is improved by the integral term. The derivative term determines the erroneous signal's rate of change and generates an output proportionate to that rate. It dampens the system's reaction and lessens oscillations and overshoot by forecasting the system's future behavior based on its current rate of change. The derivative action contributes to the system's increased stability and transient response. To get the required system response, stability, and performance, PID settings must be adjusted. There are many methods to conduct the tuning process, such as the Ziegler-Nichols method, trial and error method, and PID tuner. In this paper, the trial and error method is employed to find out the optimal value K_p, K_i, and K_d. Fig. 2 shows the closed loop control by the PID controller.

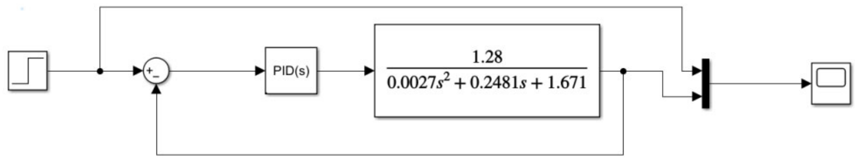

Fig. 2. PID controller utilizing the DC motor's transfer function (Photo credited: Original)

3.2 Fuzzy PID Controller

Fuzzy PID control is an advanced control method that combines the classic PID control algorithm with fuzzy logic principles to enhance the system's performance, especially under complex, nonlinear conditions. Fuzzy logic mimics human reasoning by offering a method for reasoning about imprecise or uncertain data. Rather than using the standard binary logic of true or false (1 or 0), it functions on degrees of truth by applying the membership functions. Fuzzy sets and rules are used to handle variables that have a set of truth values given to them in fuzzy logic. The process below is how the fuzzy logic integrates with the traditional PID control:

(1) Fuzzification: Using specified language sets (e.g., Low, Medium, High), the error(E) and the error's rate of change(EC) are typically the input variables that are transformed into fuzzy values.

(2) Fuzzy Rule Base: Based on empirical data or expert knowledge, a collection of fuzzy rules is developed. These rules establish the interactions between the fuzzy variables and how they modify the outputs of the PID controller.

Inference engine: In this part, through methods like Mamdani or Sugeno inference (inference mechanism). To determine the fuzzy outputs, the fuzzy inputs are subjected to the rule base.

(3) Defuzzification: Defuzzification is a crucial stage where the fuzzy conclusions generated by the fuzzy inference system are transformed back into precise, useful control outputs. To communicate with non-fuzzy control systems or to provide outputs that are comprehensible to human operators, this conversion from a fuzzy set to a single integer is required. This research uses the centroid method to elucidate the fuzzy controller's outputs.

Fig. 3 and Fig. 4 below reveal the architecture of the Fuzzy PID controller in flow chart and Matlab respectively. The inputs of the fuzzy controller are angular speed error (E) and the change rate of the error (EC). And the outputs are dK_p, dK_i, dK_d (change of K_p, K_i and K_d). After experiments, the quantization factors for E and EC are set to 1 and 0.001 respectively. The scaling factors for K_p, K_i and K_d are set to 2.9, 100, and 1 respectively. After the crisp inputs (E, EC) are converted to fuzzy sets using defined membership functions. The inference engine will apply fuzzy rules to determine the output fuzzy sets. These output fuzzy sets are transformed into specific values (dK_p, dK_i, dK_d) which are the outputs of the fuzzy controller. Then these outputs integrate with the established parameters of the conventional PID controller (K_p, K_i and K_d), modifying them to get the optimal control parameters to achieve the control of the angular speed of the DC motor. Additionally, dK_p, dK_i,and dK_d change dynamically with the E and EC. So that the optimal control parameters change dynamically. They are named as K_p^*, K_i^* and K_d^*, consist of established parameters and the outputs of the fuzzy controller as follow:

$$K_p^* = K_p + dK_p \tag{8}$$

$$K_i^* = K_i + dK_i \tag{9}$$

$$K_d^* = K_d + dK_d \tag{10}$$

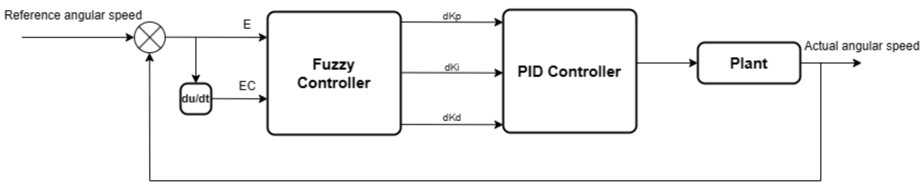

Fig. 3. Flow Chart of Fuzzy PID Controller (Photo credited: Original)

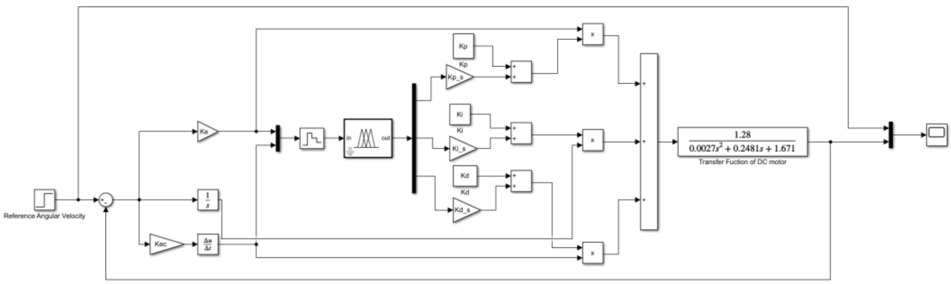

Fig. 4. Simulink Model of Fuzzy PID Controller (Photo credited: Original)

Membership Functions. A fuzzy controller is built in Matlab Simulink as shown in Fig. 5. Fig. 6 and Fig. 7 display the membership functions of E and EC. To build a rapid, stable, and robust system. Seven linguistic variables are chosen for every input and output, they are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZO), Positive Small (PS), Positive Medium (NM), and Positive Big (PB). Therefore, the fuzzy sets of E and EC are defined as{NB, NM, NS, ZO, PS, PM, PB}, mapping to the universe [-6, 6], using the Triangle membership function. Fig. 8, Fig.9 and Fig.10 show the membership functions of $\mathbf{dK_p}$, $\mathbf{dK_i}$,and $\mathbf{dK_d}$. The fuzzy sets of $\mathbf{dK_p}$, $\mathbf{dK_i}$ and $\mathbf{dK_d}$ are defined as the same as the error's too. And they are mapped to the domains [-7, 7], [-1, 1], and [-1, 1] respectively, using the Gaussian membership function.

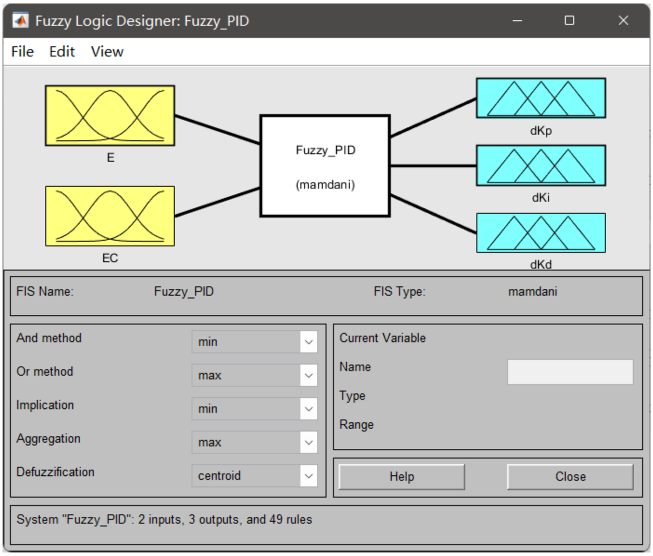

Fig. 5. Fuzzy controller (Photo credited: Original)

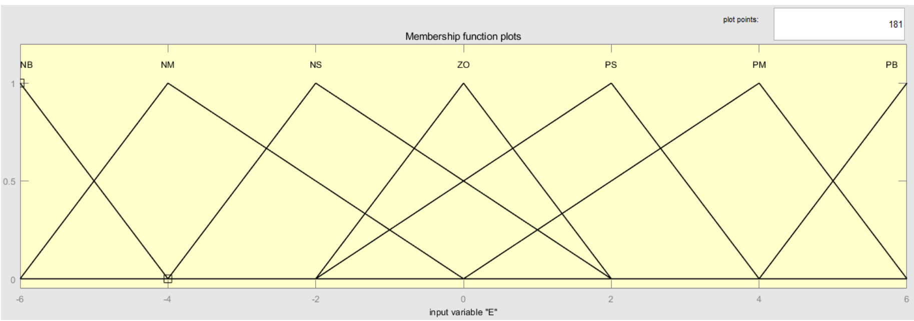

Fig. 6. Membership function of E (Photo credited: Original)

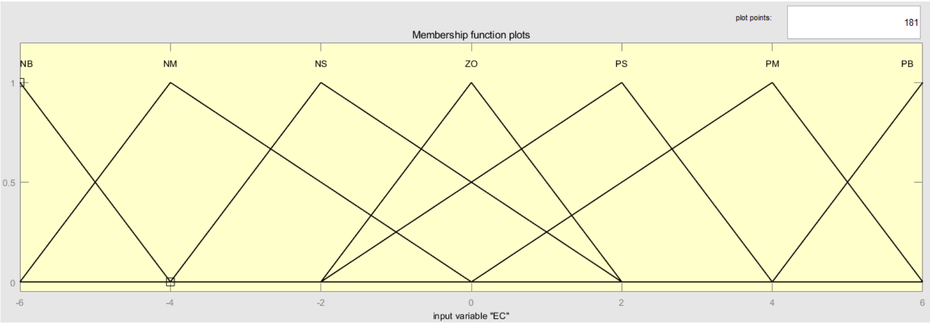

Fig. 7. Membership function of EC (Photo credited: Original)

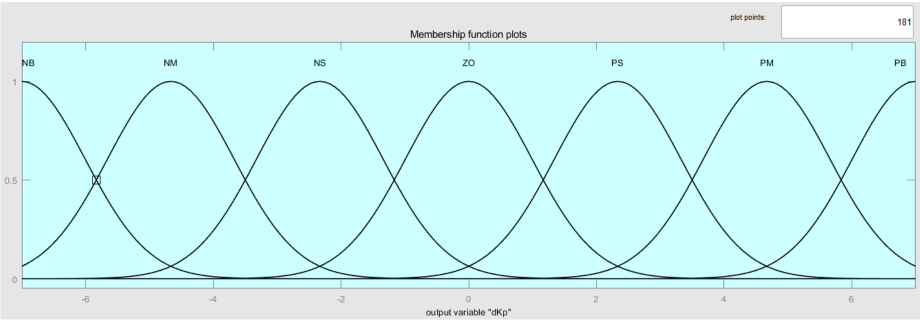

Fig. 8. Membership function of dKp (Photo credited: Original)

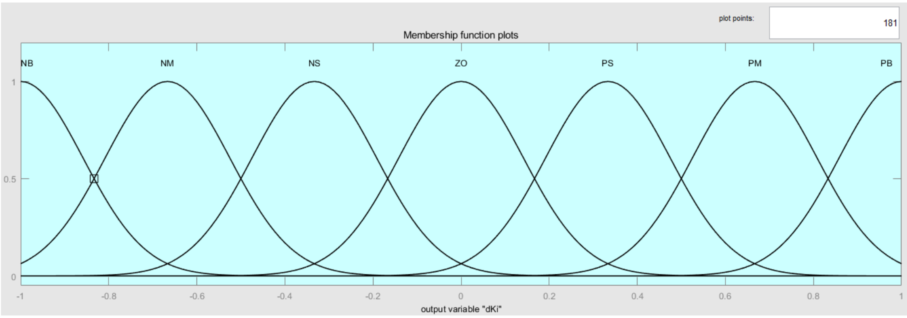

Fig. 9. Membership function of dKi (Photo credited: Original)

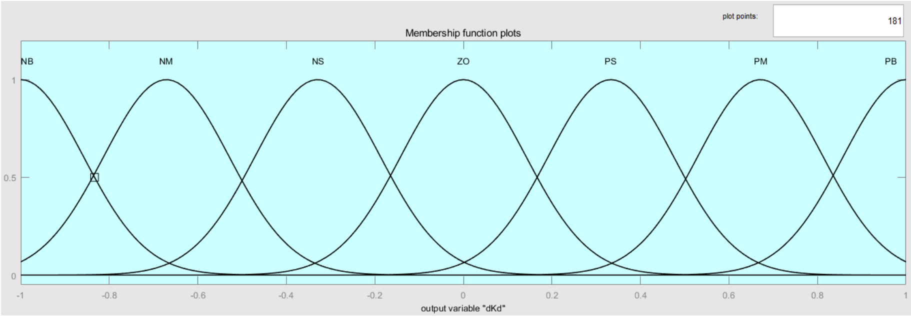

Fig. 10. Membership function of dKd (Photo credited: Original)

Fuzzy Rule Base Design. The fuzzy rules are significant in fuzzy controllers. The rules formulated by experts could directly affect the controller's performance. According to the different functions of terms P, I, and D. The rules use an "If and then" format, and the fuzzy rule chart is shown below in Table 2. The principles should be attached importance of formulating an excellent rule base for the system. Therefore, the fuzzy rules should obey the following tuning regulations.

(1) When E is comparatively big. To obtain a quick and strong response performance, K_p should be increased to speed up the motor dynamic reaction, but it looks bigger to avoid the integral saturation phenomena. K_i should be set to 0 and lower the integral intensity to address the overshoot. To avoid differential saturation, K_d should also be slightly decreased [6].

(2) When E is relatively in the middle size, K_p, K_i, and K_d should be relatively temperate to obtain an excellent system response.

(3) When E and EC are relatively small, it means the system is in a fine adjustment phase. So K_p and K_d could be increased. To stop the system from oscillating around the reference value, the value of K_d should be considered along with the value of EC. The value of K_d can be greater when EC is small, or smaller when EC is higher; typically, it is set at medium [10].

Table 2. Fuzzy Rules Chart of dKp, dKi, and dKd

E \ EC	NB	NM	NS	ZO	PS	PM	PB
NB	PB:NB:PS	PB:NB:NS	PM:NM:NB	PM:NM:NB	PS:NS:NB	ZO:ZO:NM	ZO:ZO:PS
NM	PB:NB:PS	PB:NB:NS	PM:NM:NB	PS:NS:NM	PS:NS:NM	ZO:ZO:NS	NS:ZO:ZO
NS	PM:NB:ZO	PM:NM:NS	PM:NS:NM	PS:NS:NM	ZO:ZO:NS	NS:PS:NS	NS:PS:ZO
ZO	PM:NM:ZO	PM:NM:NS	PS:NS:NS	ZO:ZO:NS	NS:PS:NS	NM:PM:NS	NM:PM:ZO
PS	PS:NM:ZO	PS:NS:ZO	ZO:ZO:ZO	NS:PS:ZO	NS:PS:ZO	NM:PM:ZO	NM:PB:ZO
PM	PS:ZO:PB	ZO:ZO:NS	NS:PS:PS	NM:PS:PS	NM:PM:PS	NM:PB:PS	NB:PB:PB
PB	ZO:ZO:PB	ZO:ZO:PM	NM:PS:PM	NM:PM:NB	NM:PM:PS	NB:PB:PS	NB:PB:PB

4 Simulation Results and Analysis

Based on the conventional PID controller built in Simulink, using the trial-and-error method, a set of initial K_p, K_i, and K_d are obtained: $K_p = 4.23$, $K_i = 50.04$, and $K_d = 0$. A step block with a final value 1 is applied as the reference angular velocity. The step response of conventional PID controllers and fuzzy PID controllers are illustrated in Fig. 11. The conventional PID is represented by the blue line, and the fuzzy PID is shown by the purple line. The figure also shows the reference angular velocity (red line) in order to analyze the time domain parameters.

The simulation results indicate that contrasted with the standard PID controller, the fuzzy PID controller performs more dynamically with reduced overshoot. This is caused by the fuzzy PID controller's shifting control parameters. The fuzzy controller determines the new PID parameters based on fuzzy rules that are best for the current situation as soon as E and EC change.

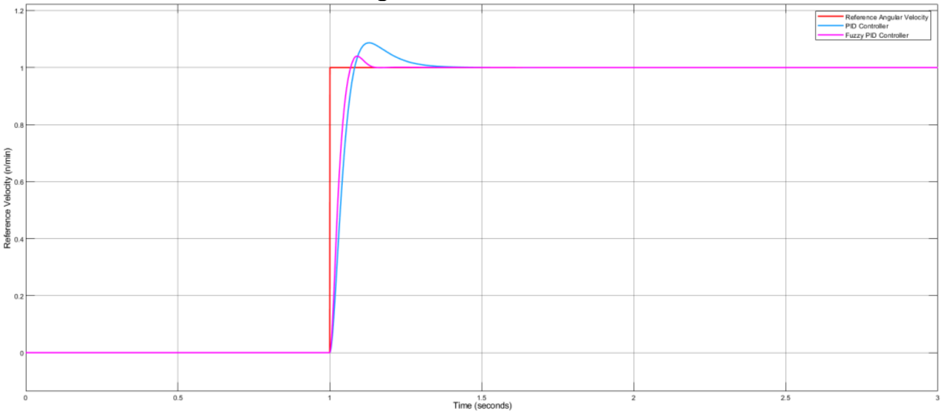

Fig. 11. The Step Response For The PID Controller and The Fuzzy PID Controller (Photo credited: Original)

The time domain parameters are computed from the step response and shown in Table. 3. Rise time and peak time imply the response speed of the system. The fuzzy PID has 21% and 31% improvements for rise time and peak time, indicating the fuzzy PID has a faster response than the conventional PID. The system's stability is shown by the transient and settling times. It is discernible that the fuzzy PID has a 100% improvement in settling time. Because the settling time is typically defined as the time the signal fluctuates within ±5% of the final value. In this experiment, the overshoot (maximum value of the signal) of fuzzy PID is 4%, therefore, the settling time of fuzzy PID is 0. Also, the fuzzy PID has a 69% improvement for transient time. These two improvements imply that the classic PID is less stable than the fuzzy PID. The overshoot of fuzzy PID is 4.0%, one time less than the traditional PID (8.7%). This feature further demonstrates the fuzzy PID's superior stability over the traditional PID.

Table 3. Comparison of two types of controllers

Time Domain Parameters	PID Controller	Fuzzy PID Controller	Improvement
Rise Time(s)	0.066	0.052	21%
Transient Time(s)	0.19	0.059	69%
Settling Time(s)	0.12	0	100%
Peak Time(s)	0.13	0.09	31%
Overshoot(%)	8.7	4.0	54%

5 Conclusion

This paper presents two Matlab Simulink models of PID controllers: a standard model and a fuzzy model. The classic PID controller and the fuzzy PID controller, respectively, are used to operate a DC motor that is represented by the transfer function. The traditional PID controller uses the trial and error method to find the optimal values of K_p, K_i, and K_d. For the fuzzy controller, membership functions and fuzzy rule base are developed under experiments and calculations. Introducing K_p, K_i, and K_d obtained by the trial-and-error method into the fuzzy controller, the new adaptive control parameters obtained. According to simulation studies, the fuzzy PID controller performs superior to normal PID controllers with regard to peak time, settling time, rise time, transient time, and overshoot. This leads to a faster system response and improved stability. In summary, it can be concluded that the fuzzy logic in conjunction with a PID controller performed better than a traditional PID controller. Moreover, the controller in conjunction with PID and additional algorithmic techniques such as genetic algorithms will be taken into consideration in further study.

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