# DESIGN OF PULSE-WIDTH MODULATION SPEED REGULATION CONTROL AND MEASUREMENT OF DIRECT-CURRENT MOTORS COMBINED WITH A SINGLE-CHIP MICROCOMPUTER

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*Direct-current (DC) motors are more stable in speed control, starting, and braking, so they are widely used in production and life. This paper briefly introduced the single-chip microcomputer and controlled the speed of DC motors based on the characteristic of the single-chip microcomputer that it can generate pulse-width modulation (PWM) signals. The PI control algorithm was used to assist in the speed control of DC motors. Finally, experimental analysis was performed to compare the designed speed regulation system with the speed control system of single-chip microcomputers with three duty cycles adjusted by the fixed step length. The results showed that when adjusting the speed of DC motors, the single-chip microcomputer speed control system with the duty cycle adjusted by the fixed step length reached the preset speed earlier with the increase of the adjustment step length, but it was also more likely to have overshoot, which reduced the speed adjustment effect; the single-chip microcomputer speed control system based on the PI control algorithm not only reached the preset speed faster but also avoided overshoot, which was more stable.*

**Keywords**: single-chip microcomputer; pulse-width modulation; direct-current motor; speed

## 1. Introduction

The application of electric power has greatly facilitated people's life, and electric motors are one of the common devices for electric power applications, which can be widely used in daily life and production, such as electric cars for transportation and electric fans for daily use [1]. Electric motors can be divided into alternating-current (AC) motors and direct-current (DC) motors according to the type of electricity they use. The former is driven by AC, and the latter is driven by DC. Compared with AC motors, DC motors are more stable in speed control, starting, and braking, and smoother in speed adjustment. Depending on the application, the speed of motors varies, and the speed needs to be adjusted

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according to the actual demand [2]. The ways to adjust the motor speed can be divided into three categories: voltage regulation of motor supply, resistance regulation of motors, and excitation regulation of motors. Adjusting the resistance can adjust the current level to achieve speed regulation, but the change in resistance will make part of the electrical energy to be converted into heat, resulting in waste. Adjusting the motor excitation can adjust the amount of force on the electric coil to achieve speed regulation, but this method is limited at both low and high speeds [3]. Therefore, it is more common to regulate the motor supply voltage to achieve motor speed regulation. Studies related to motor speed regulation are as follows. Zou et al. [4] programmed a DC motor control system in an automatic height adjustment device, designed a pulse-width modulation (PWM) DC motor control circuit, and solved its key problems in experiments. Chen et al. [5] put forward a sensorless single-chip microcomputer for a three-phase brushless DC motor, which contained an analog circuit, a digital circuit, and a frequency-voltage converter. They verified the effectiveness of the scheme through experiments. Wang et al. [6] designed a DC stepper motor speed detection system based on the P89V51 single-chip microcomputer and verified the method's effectiveness by comparing the experimental data with the theoretical data. According to the previous section, DC motor speed regulation can be realized by motor excitation [7], resistance, and voltage. The first two methods have drawbacks. Speed regulation based on motor excitation will be limited at low and high speeds [8]. Speed regulation based on motor resistance will generate additional heat. Therefore, the more common method of DC motor speed regulation is to adjust the motor supply voltage [9]. This paper used the advantage of the single-chip microcomputer that it can generate PWM signals using a simple program to achieve speed regulation of a DC motor. The relevant basic principle is as follows. The single-chip microcomputer outputs pulse signals periodically under the control of the preset program [10]. The chip will adjust the supply voltage of the DC motor after receiving the pulse signals, i.e., the supply voltage of the DC motor will change to periodic pulse voltage, which is normal sometimes and low or zero at other times in one cycle. The ratio of high/low voltage in the supply voltage of the DC motor will change by adjusting the ratio of high/low electrical level in the PWM signals; then, the average supply voltage of the DC motor will change, thus realizing speed regulation [11].

The rest of the paper is organized as follows. Section 2 introduces the flow of controlling DC motor speed by a single-chip microcomputer. Section 3 describes the experimental project and results of controlling DC motor speed by a single-chip microcomputer. Section 4 shows that when adjusting DC motor speed, the single-chip microcomputer-based speed control system that adjusted step length by the fixed duty cycle could reach the preset speed faster as the step length increased, but it was also more prone to overshoot, which weakened the speed adjustment effect; but the single-chip microcomputer-based speed adjustment system controlled by the PI control algorithm could make the motor reach the preset speed faster and avoid overshoot, which was more stable.

## 2. Speed regulation control and speed measurement of DC motors using single-chip microcomputers

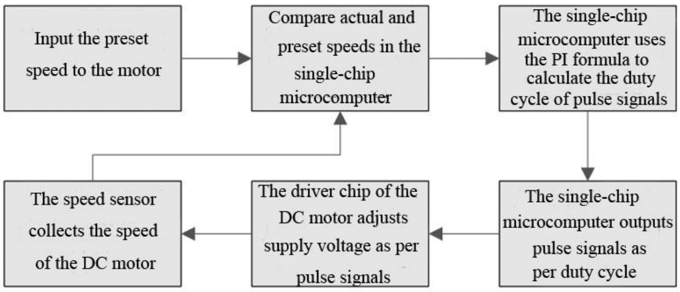


Fig. 1 The speed regulation and measurement process of a single-chip microcomputer-based DC motor

In the process of speed control of a DC motor using PWM signals of a microcontroller, the speed of the DC motor needs to be monitored. When the tachogenerator is connected to the DC motor, the rotation of the DC motor will make the tachogenerator generate a voltage. The speed of the DC motor is proportional to the voltage output from the generator, so the voltage signal from the tachogenerator can be input to the single-chip microcomputer. The speed of the DC motor can be calculated using a preset formula in the single-chip microcomputer [12].

The basic process of speed regulation and speed measurement of a DC motor by PWM signals of a single-chip microcomputer is as follows. The preset speed is input and compared with the actual speed collected by the sensor in the single-chip microcomputer. If it is lower than the preset speed, the duty cycle of pulse signals is increased according to the step length to improve the average supply voltage [13]; if it is higher than the preset speed, the duty cycle of pulse signals is decreased according to the step length to decrease the average supply voltage. The speed sensor will collect the DC motor speed in real-time during the whole speed regulation process and input it to the single-chip microcomputer.

In the above speed regulation process, the speed regulation and speed measurement of the DC motor is realized by using the duty cycle adjustment of PWM signals of the single-chip microcomputer [14]; however, in the actual use process, the duty cycle adjustment of PWM signals is just based on the positive and negative speed error. Since the duty cycle is regulated by the fixed step length, the adjustment speed is low, and the overshoot phenomenon easily occurs when the speed is close to the preset value [15]. In order to improve the efficiency and stability of DC motor speed regulation by a single-chip microcomputer, the PI control algorithm is added to the single-chip microcomputer. After adding the PI control algorithm, the speed regulation and measurement process is generally unchanged, but changes are produced in the regulation of the duty cycle. The changed process is shown in Figure 1.

Step ① The preset motor speed is input through the I/O port of the single-chip microcomputer. The real-time speed collected by the speed sensor is also input to the single-chip microcomputer through the I/O port.

Step ② The error between the actual and preset speeds is calculated using an arithmetic unit in the single-chip microcomputer.

Step ③ The controller of the single-chip microcomputer calls the PI control formula [16] in the memory to calculate the duty cycle of the PWM signal in the arithmetic unit. The traditional PI control formula for analog signal is:

$$u(t) = K_P \cdot e(t) + K_I \cdot \int e(t)dt \, , \tag{1}$$

where $u(t)$ is the output analog signal at time $t$ and $e(t)$ is the error between the analog signal at time $t$ and the signal standard. However, the single-chip microcomputer-based speed control system proposed in this paper is digital. Even if the sampling frequency is high enough to be equivalent to an analog signal, the digital signal is still discretized. Therefore, discrete adjustment is needed for the PI control formula, and the formula after adjustment is:

$$u(k) = K_P \cdot e(k) + K_I \cdot \sum_{i=1}^{k} e(i) \, , \tag{2}$$

where $u(k)$ is the output duty cycle at the $k$-th sampling point and $e(k)$ is the speed error at the $k$-th sampling point.

Equation (2) is a positional digital PI control formula. This control formula recalculates the past error state every time before adjusting the speed of DC motor, which will cause error accumulation in the long-time adjustment work and increase calculated amount. Therefore, the incremental digital PI adjustment formula is selected finally. That formula increments the output signal based on the current error and the last error, avoiding error accumulation. The corresponding formula is:

$$\begin{cases} u(k) = u(k+1) + \Delta u(k) \\ \Delta u(k) = K_P \cdot (e(k) - e(k-1)) + K_I \cdot e(k) \end{cases} , \tag{3}$$

where $u(k)$ is the duty cycle output after the current error calculation, $u(k-1)$ is the duty cycle output after the last error calculation, $\Delta u(k)$ is the duty cycle increment output after the current error calculation, $e(k-1), e(k)$ are the last and current speed errors, $K_P$ is the scale parameter, and $K_I$ is the integral parameter.

Step ④ The single-chip microcomputer outputs the PWM signals based on the calculated duty cycle.

Step ⑤ The PWM signal is transmitted to the motor driver chip. When the PWM signal has a high level, the driver chip outputs the normal motor supply voltage; when the PWM signal has a low level, the driver chip stops outputting voltage [17].

Step ⑥ The speed sensor collects the real-time speed of the DC motor, and then it returns to step ②.

## 3. Experimental analysis

### 3.1. Experimental equipment

The single-chip microcomputer used in the experiment was the STM8S003F3P6TR model of the STM8S series manufactured by STMicroelectronics. The core processor of this model was 8-bit STM8; the processing speed was 16 MHz; the program memory was eight 8kb flash memories; the capacity of EEPROM was 8 × 128 kb. The size of random access memory (RAM) was 8 × 1kb; the operating voltage was between 2.95 V and 5.5 V; the number of I/O ports was 16. A picture of the single-chip microcomputer is shown in Figure 2.

Fig. 2 The single-chip microcomputer (STM8S003F3P6TR model)

In addition to the single-chip microcomputer, a DC motor was also needed. The DC motor with model number XD-3402-1 was produced by Xinda Motor Company, which had a rated voltage of 12 V, a rated power of 30 W, an output shaft diameter of 8 mm, and a maximum speed of 3500 r/min.

The single-chip microcomputer itself did not have the function of increasing the voltage, so the voltage of its output PWM signal usually did not exceed the input voltage. The rated voltage of the DC motor used in this experiment was 12 V, and the voltage of the PWM signal output from the single-chip microcomputer was not enough to drive the DC motor, so the motor driver chip was needed to supply power to the DC motor, and the PWM signal controlled the motor driver chip to control the DC motor indirectly. A motor driver chip with model number TB6612FNG manufactured by Toshiba was used, with an operating voltage between 2.7 V and 5.5 V and an output voltage between 2.5 V and 13.5 V. The ZYS-A permanent magnet DC tachogenerator was used as the speed sensor of the DC motor.

### 3.2. Experimental setup

Figure 3 shows the basic framework of the DC motor speed regulation and measurement system built using a single-chip microcomputer. The main structure of the whole system included a host computer, a DC power supply, a single-chip microcomputer, a motor driver chip, a DC motor, and a tachogenerator. The host computer and the single-chip microcomputer were connected and exchanged information. The host computer inputs the control program and speed instruction to the single-chip microcomputer, and the single-chip microcomputer returns the monitoring parameters of the DC motor in the display of the host computer. The single-chip microcomputer was the core component of the whole system, which was powered by the DC power supply. It received the instruction from the host computer and sent the control information to the motor driver chip according to the set program; moreover, it received the information from the tachogenerator and transmitted the calculated results to the host computer. The DC power supply supplied energy to the single-chip microcomputer and the motor driver chip. The motor driver chip adjusted the voltage provided to the DC motor according to the control signal from the single-chip microcomputer under the DC power supply. The DC motor rotated under the working voltage provided by the motor driver chip and drove the tachogenerator to rotate, thus generating the electric potential. The electric potential signal generated by the tachogenerator was transmitted to the single-chip microcomputer for the calculation to obtain the DC motor speed [18].

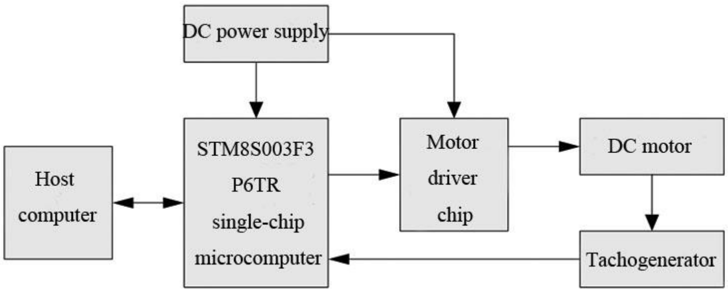


Fig. 3 The basic framework of the single-chip microcomputer-based DC motor speed regulation and measurement system

The method of generating PWM signals by the single-chip microcomputer is as follows. The cycle of the PWM signal was set as 100, and an adjustable cycle intermediate value counter was also set. The initial value of the single-chip microcomputer timer was set as 55536; the timer counts one every 1 μs. An overflow interruption happened after the timer counted 10000 times, i.e., at 10 ms; then, the timer returned to the initial value. The $t$ value whose initial value was 0 in the memory was added by one every time after the occurrence of overflow interrupt; it returned to the initial value after reaching 100. Every time $t$ was counted, it was compared with counter. The single-chip microcomputer output a high-level signal when $t$ was less than counter and a low-level signal when it was not less than counter. According to the above steps, the cycle of the PWM signal was 1 s. A cycle included two states, high level and low level. The duration of the high-level state in the cycle depended on the counter value.

In the designed speed regulation system, in addition to the program for generating PWM signals, a PI control algorithm was also added for fast regulation and speed stabilization, and the relevant formula was described in the previous section. In the PI control algorithm, scale parameter $K_P$ was set as 20, integer parameter $K_I$ was set as 2, and the regulation cycle was set as 100 ms.

In addition, as a comparison, the speed control and measurement system of the single-chip microcomputer that adopted the PI control algorithm was compared with that of the traditional single-chip microcomputer without the PI control algorithm, and the difference between the two systems only lay in the way to adjust the duty cycle of PWM signals. The traditional speed regulation and measurement system adjusted the duty cycle according to the fixed step length according to the error between the actual and preset speeds: if the error was positive, i.e., the actual speed exceeded the set speed, the duty cycle was reduced according to the fixed step length; if the error was negative, i.e., the actual speed was lower than the preset speed, the duty cycle was increased according to the fixed step length; if the error was zero, the duty cycle remained unchanged. The speed regulation performance of the system, whose duty cycle was adjusted by 1%, 5%, and 10% fixed step lengths, was tested; moreover, the system was compared with the speed regulation system of the PI algorithm-based single-chip microcomputer.

### 3.3. Experimental projects

Experimental project (1): Speed variation of the DC motor after starting at no load

The speed was set as 500 r/min in the host computer. The DC motor was started for 3 min under the no-load condition. The tachogenerator monitored the DC motor speed under the control of the single-chip microcomputer speed regulation system with different duty cycles adjusted by the step length and the single-chip microcomputer speed regulation system that adopted the PI control algorithm.

Experimental project (2): Speed variation of the DC motor after changing the preset speed at no load

The speed was set as 500 r/min in the host computer. The DC motor was started under the no-load condition. The timing started after the speed was stabilized. The preset speed was adjusted to 1000 r/min after 1 min. The DC motor speed under the control of different single-chip microcomputer speed regulation systems was also monitored in real-time using the tachogenerator.

Experimental project (3): Speed variation of the DC motor after changing from no load to load when the preset speed is set constant

The speed was set as 500 r/min in the host computer. The DC motor was started under the no-load condition. The timing started after the speed was stabilized. A load with a 5 N·m torque was added to the DC motor after an one-min operation. The DC motor speed under the control of different single-chip microcomputer speed regulation systems was also monitored in real-time using the tachogenerator.

### 3.4. Experimental results

Figure 4 shows the speed variation of the DC motor under different single-chip microcomputer speed regulation systems when starting at no load. It was seen from Figure 4 that the final speed of the no-load DC motor under the control of the four single-chip microcomputer speed control systems was stabilized at speed preset in the upper computer after starting. The speed regulation system, whose duty cycle was adjusted by 1% fixed step length, was the least efficient in regulating the DC motor speed, and it took about 60 s to stabilize the speed at the preset speed, but there was no overshoot; the speed regulation system with duty cycle adjusted by 5% fixed step length was faster, but there was overshoot, and the speed fluctuated around the preset speed and finally stabilized; the speed regulation system whose duty cycle was adjusted by 10% fixed step length was the most efficient, but the overshoot phenomenon was more significant, and even if the final DC motor speed stabilized, there were still fluctuations; the speed regulation system under PI control was slightly less efficient than the system whose duty cycle was adjusted by 10% fixed step length in speed regulation but more stable.

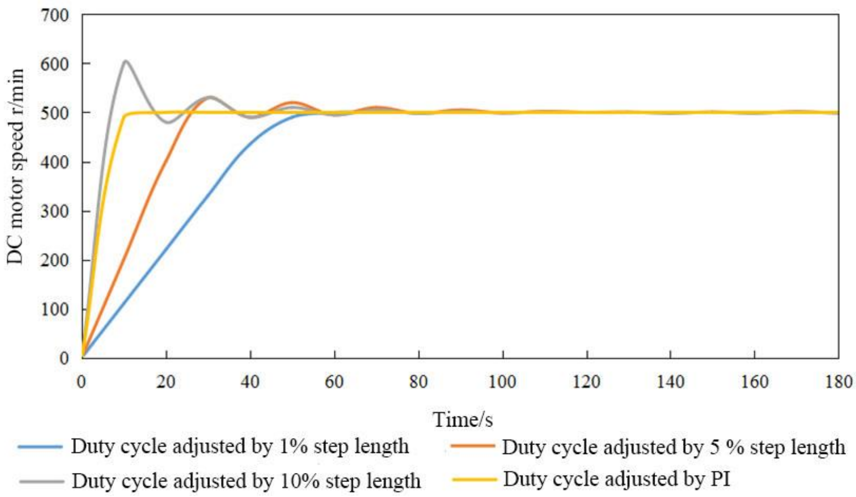


Fig. 4 Speed variation of the DC motor under the control of different single-chip microcomputer speed regulation systems after starting at no load

Figure 5 shows the speed change of the DC motor under the control of different single-chip microcomputer speed regulation systems after changing the preset speed when the speed was stable for 1 min. It was seen from Figure 5 that after changing the preset speed, the speed of the DC motor under the control of all four speed regulation systems finally stabilized at the new preset speed. In the process of speed increase, the speed regulation system, whose duty cycle was adjusted by the fixed step length, became more and more efficient in regulating the speed as the fixed step length increased, but the overshoot was also more obvious so that it took more time to stabilize the speed; the speed regulation system using PI control regulated the DC motor speed quickly and stably.

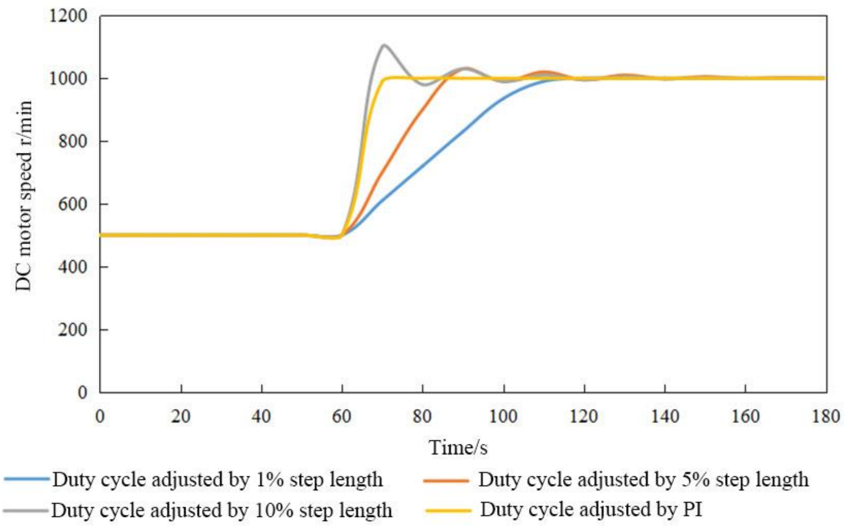


Fig. 5 Speed variation of the DC motor at no load under the control of different single-chip microcomputer speed regulation systems when the preset speed is changed

Figure 6 shows the speed variation of the no-load DC motor after increasing the load when the speed was stable for 1 min under the control of different single-chip microcomputer speed regulation systems with constant preset speed. It was seen from Figure 6 that when the load on the DC motor increased, the original supply voltage made the torque that the motor could provide insufficient to support the increased load, so the speed of the DC motor decreased under all four speed regulation systems. The speed regulation system, whose duty cycle was adjusted by 10% fixed step length, was fast, so the speed increased after a slight decrease, but the overshoot phenomenon was serious, and it took a longer time to return to the preset speed. The speed regulation system, whose duty cycle was adjusted by 5% fixed step length, was less efficient, so the speed was reduced much, but the overshoot phenomenon was not significant, so the speed fluctuated less and returned to the preset speed more quickly. The speed regulation system, whose duty cycle was adjusted by 1% fixed step length, was the weakest in regulating the speed, so the speed decreased the most and returned the slowest, but there was almost no overshot. The regulation ability of the speed regulation system under PI control was only weaker than the speed control system whose duty cycle was adjusted by 10% fixed step length, but there was no overshoot, and the motor with this system returned to the preset speed steadily.

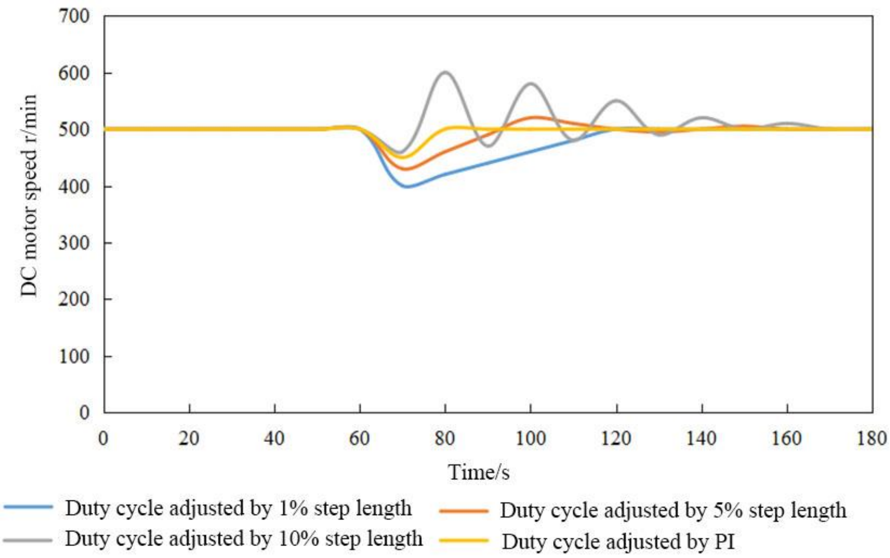


Fig. 6 Speed variation of the DC motor under the control of different single-chip microcomputer speed regulation systems after increasing the load from zero

## 4. Conclusion

This paper briefly introduced the single-chip microcomputer, utilized its characteristic that it could generate PWM signals to control the speed of DC motors, used the PI control algorithm to assist in the control of DC motor speed, and conducted an experimental analysis to compare the designed system with three single-chip microcomputer speed regulation system whose duty cycle was adjusted by different fixed step lengths. The results are shown below. When the DC motor was started at no load, the speed regulation system, whose duty cycle was adjusted by the fixed step length, became more efficient in regulating the speed with the increase of the step length, but the overshoot phenomenon was significant, and the speed regulation system under PI control quickly and stably reached the preset speed. When the preset speed changed, the speed regulation system, whose duty cycle was adjusted by the fixed step length, was faster in regulating the speed with the increase of the step length, but the overshoot phenomenon was significant, and the PI-controlled speed regulation system quickly and stably reached the new preset speed. When the load on the DC motor increased, the DC motor’s speed under the control of all four speed regulation systems decreased, while the PI-controlled speed regulation system quickly and steadily returned to the preset speed.

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