

Positioning-control Based on Trapezoidal Velocity Curve for High-precision Basis Weight Control Valve

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Abstract: Traditionally, basis weight control valve is driven by a constant frequency pulse signal. Therefore, it is difficult for the valve to match the control precision of basis weight. Dynamic simulation research using Matlab/Simulink indicates that there is much more overshoot and fluctuating during the valve-positioning process. In order to improve the valve-positioning precision, the control method of trapezoidal velocity curve was studied. The simulation result showed that the positioning steady-state error was less than 0.0056%, whereas the peak error was less than 0.016% by using trapezoidal velocity curve at 10 positioning steps. A valve-positioning precision experimental device for the stepper motor of basis weight control valve was developed. The experiment results showed that the error ratio of 1/10000 positioning steps was 4% by using trapezoidal velocity curve. Furthermore, the error ratio of 10/10000 positioning steps was 0.5%. It proved that the valve-positioning precision of trapezoidal velocity curve was much higher than that of the constant frequency pulse signal control strategy. The new control method of trapezoidal velocity curve can satisfy the precision requirement of 10000 steps.

Keywords: high-precision basis weight control valve; precision positioning control; trapezoidal velocity curve; Matlab/Simulink simulation

1 Introduction

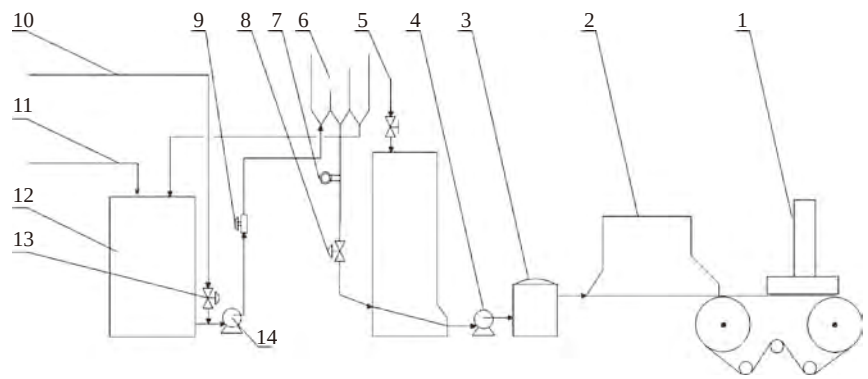
High-precision basis weight control valve is a key actuator for basis weight during

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papermaking process^[1]. It is mounted on the pipeline of the pulp tank, as shown in Fig.1. The pulp consistency is accurately controlled by the consistency control loop. The pulp flowrate is controlled by using a high-precision basis weight control valve. The basis weight of a paper is the product of pulp consistency and mass flowrate. The paper basis weight signal is measured by a scanner. The quantity control system (QCS) adjusts the pulp consistency and mass flowrate automatically. Basis weight is controlled by this technological process.

The basis weight control valve is driven by a stepper motor through a planetary reducer to enlarge torque and turn the spool to adjust pulp flowrate. The typical high quality basis weight control valves are Neles ACE of Metso^[2] and VBW-1100 of BTG^[3]. These basis weight control valves can reach 10000~25000 steps precision, but they are too expensive for paper mills to acquire. Researchers in China have done a lot of research to develop the domestic production. A model machine of basis weight control valve was designed by Wang's research group^[4]. And the valve-positioning precision was tested. The results showed that there were some errors in positioning precision, which could not match with the requirements of advanced application. To achieve the objective of 10000 steps precision, some research is needed to carry out to study the error mechanisms, and find a way to improve the positioning precision of the basis weight control valve.

This paper introduced the mechanical structure of basis weight control valve, and calculated the mechanical parameters of the valve. Traditionally, the stepper motor which drives the basis weight control valve is based on a constant frequency pulse signal. The positioning control strategy of the constant frequency pulse signal was simulated by using Simulink, and the error mechanism was analyzed. A trapezoidal velocity curve based on the control algorithm was



1—Scanner; 2—Headbox; 3—Pressure screen; 4—Fan pump; 5—White water; 6—Pulp tank; 7—Flow transmitter; 8—High-precision basis weight control valve; 9—Consistency transmitter; 10—White water; 11—Pulp; 12—Pulp storage; 13—Consistency regulatory valve; 14—Pulp pump

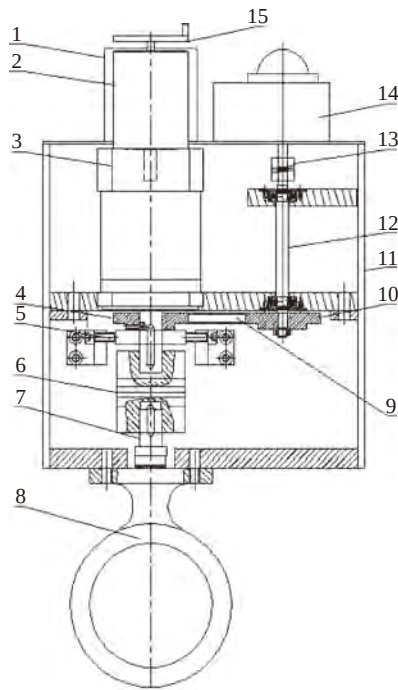
Fig.1 Application of high-precision basis weight control valve during papermaking process

presented. Simulation results showed that the new algorithm could reduce the error of motor positioning process. In order to test whether the new algorithm was effective, a positioning precision experimental device was designed. The experimental test results confirmed that the new control strategy was more effectively and accurately than the constant frequency pulse signal control strategy.

2 Mechanical structure and control strategy of high-precision basis weight control valve

The high-precision basis weight control valve is made up of an actuator, a V-type ball valve, and a dedicated controller, as shown in Fig.2^[5]. The stepper motor is fitted on a planetary reducer, and the planetary reducer is fixed on a support plate. The ball valve and the actuator are bound together through screw bolts. The torque is transmitted by a high-rigidity coupling, which connects the valve stem and the reducer's output shaft together. A valve position indicator is installed on the top of the actuator shell. The upper QCS sends a pulse signal to the valve controller to drive the movement of the stepper motor.

The rotation range of the actuator is $0\sim90^\circ$. Because the planetary reducer has a transmission ratio of $200:1$, the rotation range of the stepper motor is $0\sim18000^\circ$ (50 turns). The two-phase stepper motor drives the valve with a 1.8° step angle. One full valve



1—Stepper motor cover; 2—Stepper motor; 3—Planetary reducer; 4—Driving synchronizing wheel; 5—Mechanical limits; 6—Coupling; 7—Valve shaft; 8—V-type ball valve; 9—Synchronous belt; 10—Driven synchronizing wheel; 11—Shell; 12—Connecting shaft; 13—Coupling; 14—Valve position monitoring switch; 15—Hand wheel

Fig.2 Mechanical structure of high-precision basis weight control valve

stroke is equivalent to 10000 pulses, as the stepper driver mode is set at “full step”. The standard actuating period is 200 s, and the control pulse-frequency is 50 Hz.

Traditionally, the basis weight control valve has two kinds of control mode — pulse duration mode and time duration mode. The pulses, which are sent to the stepper driver, are constant frequency pulse sequences. The positioning precision of the valve is poor, because it is required to overcome the resistance torque and large rotor inertia of the motor, the reducer, and the valve during the acceleration stage for a very short time to reach the required speed and position. Due to the high speed, the rotation degree of the motor cannot match the pulse signal, which causes a “losing step”. Likewise, “overshoot” occurs during the deceleration stage. The error ratio of positioning process is unpredictable in advance, which leads to precision loss. With the qualitative analysis, further research should be carried out to find the reason of precision loss and

propose a way to improve the positioning precision of basis weight control valve^[6].

3 Modeling and simulation of basis weight control valve

Valve positioning errors mostly occur at moments of speed-change, such as accelerating and decelerating process. On the contrary, there is less error for smoothly running during the period of constant velocity. It is difficult to snap the phenomenon of losing step in a split-second by regular instruments. Take an example of the valve with action time 200 s and 10000 steps. It is an instantaneous period with a least step width of 0.02 s. The phenomenon of losing step commonly occurs at the moment of control pulse rising or falling edge. The time it lasts is nearly a microsecond, which is much shorter than the time resolution of regular instruments^[7]. Instruments with higher time resolution are very expensive. Matlab simulation is helpful in reducing the cost of research work, because it has a stepper motor simulation model which can study the detail rotation angle during the positioning process. The basis weight control valve can be simplified as a stepper motor with load. The rotation angles during the positioning process can be obtained through simulation. Steps for establishing a simulation model are listed as follows^[8-9].

(1) Calculate the load torque of motor rotating shaft, which is equivalent to the resistance torque of basis weight control valve.

(2) Calculate the rotor inertia of motor rotating shaft, which is equivalent to the rotor inertia of basis weight control valve.

(3) Confirm the electrical parameters of the stepper motor driver, and then input the parameters to the simulation model.

(4) Use the Simulink signal generator to send pulses of control signal to the stepper motor driver. Simulation results can be collected by Simulink scope, and then a detailed research can be carried out to explore the mechanism of positioning errors.

Simulation analysis can obtain detail data, such as the corresponding relationship between rotation angle

and time during the full movement process, especially at the starting and stopping moments at which losing step or overshoots occur. In order to find a way to improve the positioning precision of basis weight control valve, important data are collected and analyzed.

3.1 Analysis of mechanical parameters

The parameters of Simulink model should be consistent with those of the basis weight control valve. The mechanical parameters such as load torque and rotor inertia of the basis weight control valve are calculated. Detail analysis of DN125 valve are shown as follows.

(1) The rated load torque of the value is $250 \text{ N} \cdot \text{m}$, the reduction ratio (n) of the planetary reducer is $200 : 1$, so the load torque equivalent to the motor shaft is $1.25 \text{ N} \cdot \text{m}$.

(2) The total rotor inertia of the basis weight control valve equals the sum rotor inertia of its rotating parts (stepper motor, reducer, coupling, and valve shaft). According to the manual, the rotor inertia of stepper motor (J_M) is $2.7 \text{ kg} \cdot \text{cm}^2$. The rotor inertia of planetary reducer (J_R) is $1.15 \text{ kg} \cdot \text{cm}^2$. The rotor inertias of coupling (J_C) and valve shaft (J_V) are $15 \text{ kg} \cdot \text{cm}^2$ and $28 \text{ kg} \cdot \text{cm}^2$, respectively.

The rotor inertias of coupling and valve shaft equivalent to that of the motor's shaft should be divided

by the square of the reduction ratio^[10]. Therefore, the total rotor inertia (J) can be calculated as follows.

$$J = J_M + J_R + (J_C + J_V)/n^2 \quad (1)$$

The calculated result of the total rotor inertia is $3.85 \text{ kg} \cdot \text{cm}^2$.

3.2 Development of Simulink model

The Simulink model of basis weight control valve is equivalent to a stepper motor with load. The model is shown in Fig.3^[11-13]. It is made up of a signal builder, a stepper driver, a stepper motor, a power, and a scope. The port STEP of the stepper driver receives the control pulse signal from the signal builder to drive the running of the stepper motor. The voltage is set by ports V+ and V-. And then, the load torque is set by port T_L . The relationship between rotation angles and time axes can be recorded and stored by Simulink scope^[14]. The electrical parameters of the stepper motor in this study are shown in Table 1.

4 Positioning control strategy of high-precision basis weight control valve

4.1 Simulation of constant frequency pulse

The precision of basis weight control valve is expressed as the number of steps. Take 10000 steps for instance, the ball of basis weight control valve,

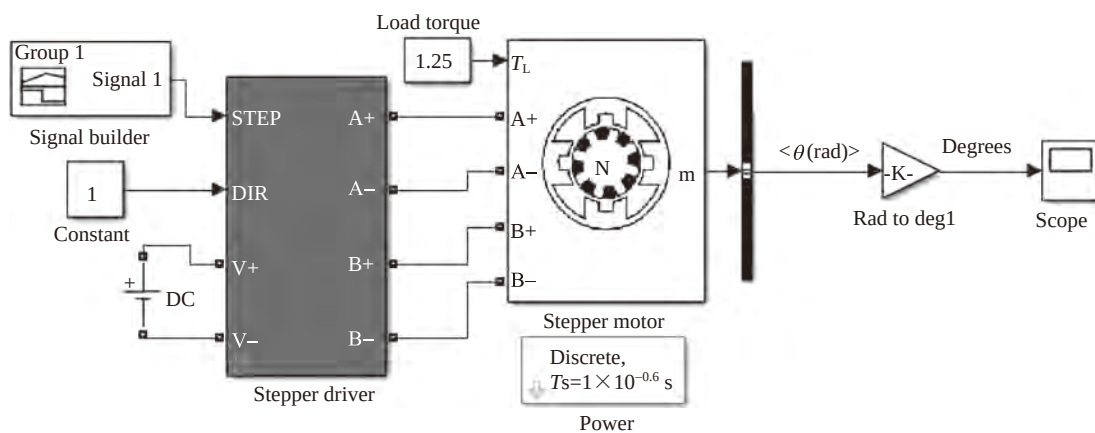


Fig.3 Simulink model of stepper motor

Table 1 Electrical parameters of stepper motor

Model of motor	Number of phase	Phase current /A	Phase resistance / Ω	Phase inductance /mH	Holding torque /(N · m)	Detent torque /(N · m)	Rotor inertia /(kg · cm ²)
86 BYG	2	5.5	0.46	31.5	4.6	0.16	2.7

going from fully closed to open, takes time for 200 s. The minimum operating time is 0.02 s, which implies that the frequency of the control pulses is 50 Hz. As an example, 10 pulses with a constant frequency of 50 Hz are sent to the Simulink stepper driver. The stepper driver is set as “full step” mode. The simulation result is shown in Fig.4.

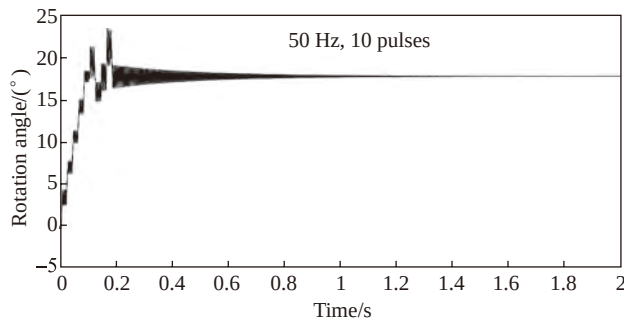


Fig.4 Simulation result of constant frequency pulse

Simulation results showed that the shaft of the stepper motor rotated 17.87° until it nearly reached the stable state. This indicated that the motor rotated 1.787° per pulse and the theoretical value was 1.800° per pulse. The steady-state error was 0.73%, this showed there was still a static error. The maximum rotation angle was 23.57° and the theoretical value was 18.00° . The maximum error was 31.93%, this implied that there was a large overshoot error. The output value at the steady state was less than 5% with a delay of 0.135 s until the control pulses were stopping. The transient period was nearly seven times longer than the minimum operating time, which implied there was a long transient time to reach the stable state.

Simulation results showed that there were the phenomena of losing step, overshoot, long transient period during the positioning process. The defects of the constant frequency pulse signal control strategy were discovered. This strategy causes the precision loss of basis weight control valve. Therefore, other more effective strategies are needed to carry out to improve the positioning precision of a stepper motor.

4.2 Study of trapezoidal velocity curve control strategy

Irregular rotary movement always occurred at the

starting and stopping moments of the stepper motor. It is the main reason of losing step and long transient time. Therefore, the positioning precision will be improved if the speed of the stepper motor changes smoothly.

It is expected that the basis weight control valve achieves higher precision with more steps^[15] if the stepper motor has enough accuracy during every minimum step. As the stepper motor shaft rotates 1.8° per pulse at full step mode, a micro-step is adopted as a division of one full step in order that it makes the stepper motor to run smoothly. The method of 6400 pulses per revolution (32 micro-steps) is suitable for most applications according to the stepper motor manual. Therefore, the stepper motor of basis weight control valve rotates 0.05625° per pulse at 32 micro-steps mode. It means that sending 32 pulses can drive the stepper motor to rotate 1.8° , which equals the value of 1/10000 positioning steps. The control strategy of accelerating and decelerating with 32 pulses is adopted to make the stepper motor run more smoothly, thereby improving the positioning precision.

Common control strategies of velocity curves include the trapezoid alvelocity curve, S-shaped velocity curve, exponential velocity curve, and parabolic velocity curve^[16-19]. The trapezoidal velocity curve control strategy is widely used because it has obvious advantages such as rapidity and accuracy performances. The control strategy has the characteristic of the constant acceleration magnitude. The stepper motor accelerates to maximum velocity with constant acceleration from a standstill state. Similarly, the stepper motor decelerates to a stop with constant acceleration from a maximum velocity. Both acceleration and deceleration motions of the basis weight control valve with the trapezoidal velocity curve are shown in Fig.5.

The whole positioning process is comprised of three critical stages. The stepper motor of basis weight control valve rotates with constant acceleration at the first stage (Stage I) and reaches the maximum velocity

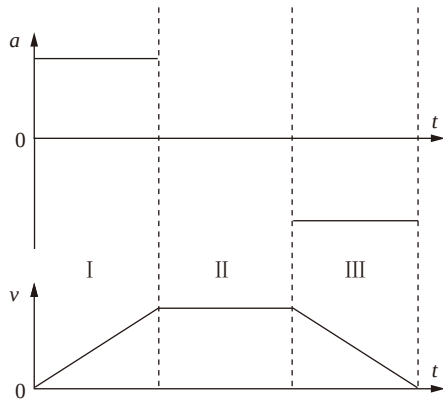


Fig.5 Trapezoidal velocity curve motion of basis weight control valve

($v_{\max}$) at the end of this stage. Then at the second stage (Stage II), the stepper motor moves with constant velocity at the maximum velocity. At the third stage (Stage III), the stepper motor decelerates until it stops with constant acceleration. In order to simplify the calculation process, the absolute value of acceleration (a) at the acceleration and deceleration stages was set as the same value. The time (T_0) of the acceleration and deceleration stages was also set as the same value. The processes of accelerating and decelerating were symmetrical, including velocity, acceleration, and time. The stepper driver was set as 32 micro-steps. It took 16 pulses to achieve uniformly accelerating motion with a time of T_0 . Similarly, it took another 16 pulses to achieve uniformly decelerating motion with a time of T_0 . The total rotation angle of the stepper motor at accelerating and decelerating stages was 1.8° . The time duration was 0.02 s, which equaled the minimum operating time of the original full step mode. Therefore, the time of accelerating and decelerating stages was $2T_0$. The time of accelerating stage was T_0 , and the time of decelerating stage was also T_0 . As the operating units must be integers, the time of the constant velocity motion stage is $(n-1)T_0$. The total operating time of the positioning process is shown as follows.

$$T = \begin{cases} 2T_0 & n=1 \\ (n+1)T_0 & n \geq 2, n=Z \end{cases} \quad (2)$$

The stepper motor accelerates to the maximum velocity at the end of the acceleration stage. The

constant velocity of the trapezoidal velocity is equal to the original velocity of rotation in the full-step driving mode. The angular velocity (v_{II}) of the stepper motor is $90^\circ/\text{s}$, and the stepper driver is set as 32 micro-steps. The stepper motor moves with a stepping angle (StepAngel₃₂) of 0.05625° . The accelerating stage duration is T_0 , and the decelerating stage duration is also T_0 . The control pulse frequency (f_{II}) can be expressed as follows.

$$f_{II} = \frac{v_{II}}{\text{StepAngel}_{32}} \quad (3)$$

Calculating, the control pulse frequency of constant velocity stage (f_{II}) is 1600 Hz.

The generating pulse method of the accelerating stage was studied. Then, the time of decelerating stage was obtained according to the symmetrical relationship of accelerating stage. The stepper motor rotates with a fixed intermittent angle when a control pulse is generated. The curves of velocity-time and rotation angle-time are shown in Fig.6.

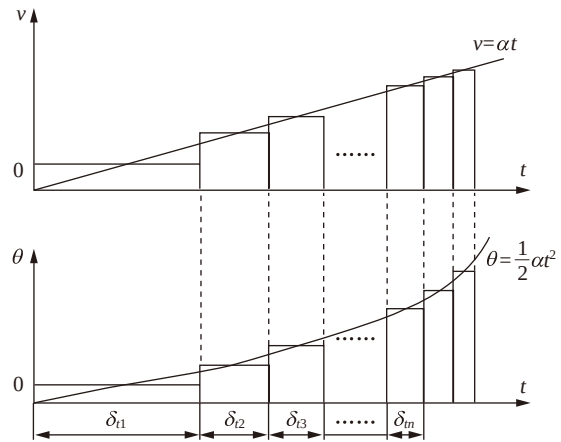


Fig.6 Velocity-time and rotation angle-time curves

The time interval is defined as the time between each pulse generated in sequence ($\delta_{t1}, \delta_{t2}, \dots, \delta_{tm}$). The letter n represents the n th pulse generated. The rotation angle of each pulse generated is expressed as Eqs.(4) and (5).

$$\theta_n = \frac{1}{2}a(\delta_{t1} + \delta_{t2} + \dots + \delta_{tm})^2 \quad (4)$$

$$\theta_{n-1} = \frac{1}{2}a(\delta_{t1} + \delta_{t2} + \dots + \delta_{t(n-1)})^2 \quad (5)$$

The difference value of θ_n and θ_{n-1} is equal to the

micro-step angle (0.05625°). The relationship of the time interval between the n th pulse and $(n-1)$ th pulse obeys the following formula (Eq.(6))^[20].

$$\frac{\delta_{tn}}{\delta_{t(n-1)}} = \frac{\sqrt{n} - \sqrt{n-1}}{\sqrt{n-1} - \sqrt{n-2}} \quad (n \geq 2) \quad (6)$$

The time interval between n th pulse and $(n-1)$ th pulse from the 1st pulse to 16th pulse is shown as follows.

$$\delta_{t1} : \delta_{t2} : \delta_{t3} : \dots : \delta_{t16} = 1 : (\sqrt{2}-1) : (\sqrt{3}-\sqrt{2}) : \dots : (\sqrt{16}-\sqrt{15}) \quad (7)$$

The total time of the accelerating stage (Stage I) is 0.02 s which equals the sum of the time intervals. Then, the time interval between n th pulse and $(n-1)$ th pulse can be calculated out according to Eq.(8). The time interval of each pulse at the decelerating stage (Stage III) is obtained for the symmetrical relationship of the accelerating stage. The time interval of each pulse at the constant velocity stage (Stage II) is 0.625 ms. Take the motion of 10 steps positioning process, for instance, 16 pulses with pulse-width decreasing were sent to the stepper driver to speed up the stepper motor to reach the maximum velocity during 0.02 s with the rotation angle of 0.09° . Secondly, a constant frequency pulse with periods of 0.625 ms was generated for 0.18 s to complete the constant velocity stage motion. Finally, another 16 pulses with pulse-width increasing were generated to make the stepper motor to stop during 0.02 s with the rotation angle of 0.09° . The time of whole positioning process was 0.22 s. The pulse distribution in 10 steps was shown in Fig.7.

$$\delta_{t1} + \delta_{t2} + \delta_{t3} + \dots + \delta_{t16} = T_0 \quad (8)$$

The result of simulation using the new control strategy of micro-step and trapezoidal velocity curve was stored by Matlab software. The performance comparison of constant frequency pulse signal control strategy and trapezoidal velocity curve control strategy is shown

in Fig.8. The rotation angle at the steady state is 17.999° , and the theoretical value is 18.000° . The results illustrate that the steady state error is less than 0.0056%, which is very small. With detailed analysis of the stored data, the maximum rotation angle is 18.003° , so the overshoot is very little. Compared with the constant frequency pulse signal control strategy, the trapezoidal velocity curve control strategy possesses the following advantages:

(1) The steady state error is less than 0.0056%. It illustrates that the valve-positioning precision is high and the trapezoidal velocity curve control strategy has good static performance.

(2) The maximum peak error is less than 0.017%. It illustrates that the transient time is very short, and the trapezoidal velocity curve control strategy has good dynamic performance.

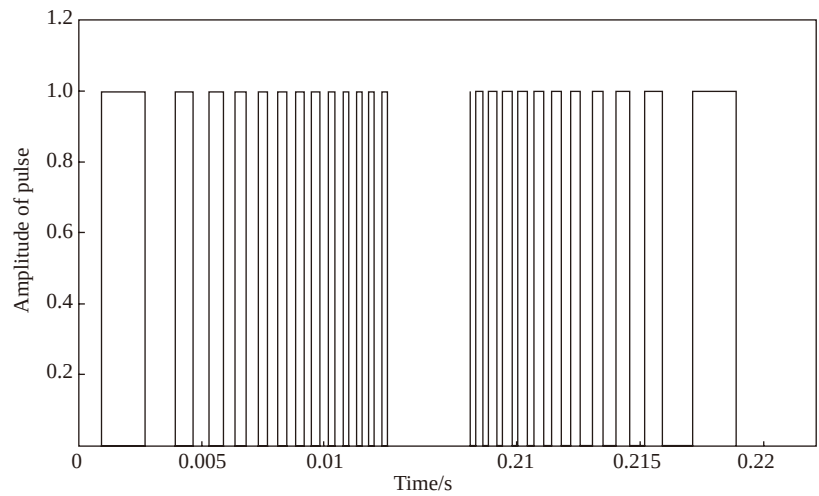


Fig.7 Pulse sequence of trapezoidal velocity curve

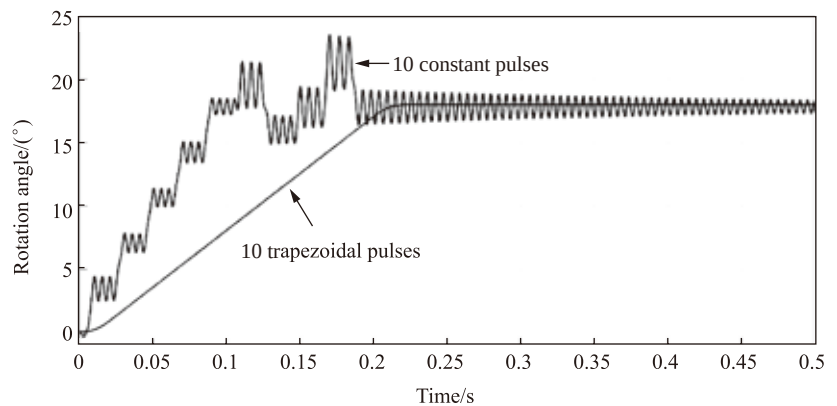


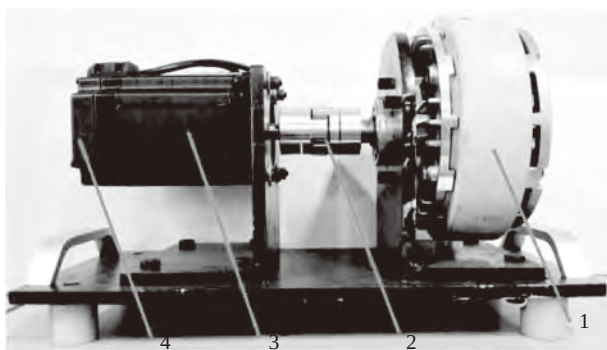
Fig.8 The performance comparison of trapezoidal velocity curve control strategy and constant frequency pulse signal control strategy

5 Experimental tests

Simulation study results showed that the control strategy of the trapezoidal velocity curve could increase the control precision. In order to inspect and verify actual functions of the new control strategy, a valve-positioning precision experimental device of stepper motor was developed. The mechanical structure of the device is shown in Fig.9. The device is mainly made up of a stepper motor, magnetic powder brake and control system. The stepper motor is used to provide rotating torque, while a high-precision rotary encoder (with 4000 pulse/r) is mounted on the stepper tail shaft that can measure rotation angle of the stepper motor. The magnetic powder brake provides resisting torque which is equivalent to the load torque of basis weight control valve. The control system generates pulse signals and measures the rotation angle of the stepper motor and stores the test data.

The positioning steps of 1/10000, 2/10000, 5/10000, and 10/10000 at full travel range were tested. The result of each positioning process is shown in Table 2.

Test results show that the error of the actual positioning precision is very low. The error of 1/10000



1-Magnetic powder brake; 2-Coupling; 3-Stepper motor; 4-Encoder

Fig.9 Valve-positioning precision experimental device of stepper motor

Table 2 Positioning precision experimental data

Positioning steps	Theoretical feedback value of encoder	Actual feedback value of encoder at 5 times test						Error /%
		1 [#]	2 [#]	3 [#]	4 [#]	5 [#]	Average value	
1/10000	20	22	19	22	21	22	21.2	4.0
2/10000	40	41	42	41	42	42	41.6	4.0
5/10000	100	103	102	102	102	102	102.2	2.2
10/10000	200	202	201	198	202	202	201.0	0.5

positioning steps is 4.0%, which can satisfy error limitation of less than 5%. Moreover, the error of 10/10000 positioning steps is 0.5%. So the error will be lower with the increase of positioning steps.

6 Conclusions

Both simulation and experimental tests carried out by experimental platform show that the new control strategy of the trapezoidal velocity curve has sufficient precision for 10000 steps. The follow-up practical application of a high-precision basis weight control valve also proved that the control strategy of the trapezoidal velocity curve was effective. Furthermore, the original control system can use the new and effective control strategy only by updating the software without any change of hardware, which is useful for the previously sold products in the market.

Although the new control strategy can improve the valve-positioning precision, further research is needed. In order to reduce the impact of backlash of the mechanical parts, an expensive high-precision planetary gear reducer is needed, in which backlash is very small. The mechanical backlash of a valve has great influence on the positioning precision, so an expensive high-precision planetary gear reducer must be selected to ensure the valve-positioning precision. If the mechanical backlash can be compensated by software, a cheaper gear reducer can be chosen. Furthermore, careful research is needed for other types of motors, for example, a servo motor has much higher precision than a stepper motor.

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