Investigation on positioning control strategy and switching optimization of an equal coded digital valve system

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Abstract

This paper concerns high accuracy positioning control with switching optimization for an equal coded digital valve system. Typically, PNM (Pulse number modulation) control can't realize micro-positioning due to the characteristics of step-wise flow variation, therefore, a new position controller consisting of a model-based PNM and a DPWM (Differential pulse width modulation) strategy is proposed to control the position of a hydraulic cylinder at high and low velocity cases, respectively. In addition, in order to solve several problems caused by the PNM and DPWM, such as increased number of switchings and large difference among number of switchings of valves, a switching optimization consisting of a switching cost function, a circular buffer and a circular switching method is proposed. An adaptive weight of the switching cost function is proposed for the first time to reduce the total number of switchings under different pressure differences and its design criterion is presented. A circular buffer and a new circular switching method are used to improve the degree of equal distribution of switchings when the PNM and DPWM are used, respectively. Comparative experimental results indicated that the average and the minimum positioning error for the proposed controller are only 10 µm and 1 µm, respectively. The number of switchings and the degree of equal distribution of switchings are significantly optimized. Moreover, the pressure fluctuations caused by the proposed controller remain acceptable.

Keywords

Digital hydraulics; Differential PWM; Adaptive switching cost function; Circular buffer; Circular switching

1. Introduction

The electro-hydraulic servo systems (EHSS) are widely used in construction and agricultural machinery, robots, and aircraft actuators due to their high precision, higher power density and high frequency response [1-3]. However, the disadvantages of the EHSS include high cost, high power consumption, and low reliability because of using servo valves which are sensitive to oil contamination. Nowadays, digital hydraulic systems composed of several on/off valves are considered to provide competitive alternative technologies to the EHSS due to their low throttling losses, low cost and high reliability [4-6]. Additionally, an intelligent system capable of real-time monitoring and fault diagnosis can be easily embedded in the digital hydraulic system using simple and robust hardware which makes it fit for the industry 4.0 [7].

Wang [8] classified the digital hydraulic systems into three types. The first type is the traditional on/off hydraulic technology in which the output of the system can only have two discrete values. The system is robust and tolerant. The second type is the high frequency switching hydraulic system in which the "analog output" is obtained by the fast switching of the on/off valve. The benefit of this technology is that the proportional flow can be achieved by one fast on/off valve; but, severe pressure fluctuations are likely to occur in the system. Typical applications of this technology include hydraulic buck converter [9], antilock braking systems (ABS) [10] and fuel injectors [11]. The third type is the digital valve-controlled system based on parallel connection in which the discrete output is achieved by coding the combination of on/off valves. The flow resolution of the system is determined by the number of parallel connected on/off valves Typical applications of this technology include DFCU (Digital Flow Control Unit) [12], DHPMS (Digital Hydraulic Power Management System) [13, 14], and DHHA (Hydraulic Hybrid Actuator) [15]. Compared to the second type (high frequency switching hydraulic systems), the parallel connection digital hydraulic systems have more advantages in scalability, programmability and reliability [16].[1]

However, the parallel connection digital valve-controlled systems still needs to be improved to meet the requirements of high precision applications; especially by improving the positioning accuracy, optimizing the switching life time and alleviating pressure fluctuations. Linjama and Vilenius [17] first proposed a model-based controller and a direct search method to find the best flow combination of the DFCU. In the study, the switching cost function was used to find a compromise between the accuracy and the number of switchings. But, the weight of the switching cost function still needs to be tuned for different flow conditions. Wang et al. [18] applied a model-based control strategy to a separate meter-in and separate meter-out digital valve-controlled system. The results showed that the position accuracy can be controlled within 2 mm. Long and Lumkes [19] presented a pulsing method in which inflow side and outflow side on/off-

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valves work alternately to achieve a stepping-like displacement of a hydraulic cylinder, which improves the displacement resolution. Huova and Plöckinger [20] designed a controller that combines PCM (Pulse code modulation) and PWM (Pulse width modulation) to improve the flow resolution of a DFCU. Huova et al. [21] proposed a fine positioning method of a binary DFCU based on the injection of predetermined fluid volume by opening on/off-valves for the correct time period. In this method, the smallest on/off valve is the most used, which makes it more prone to fatigue wear compared to other on/off valves.

However, almost all of the above studies focused on the problem of how to improve the positioning accuracy of a DFCU, but few works concentrated on how to optimize the life time of valves by distributing the number of switchings among all valves equally or with the smallest differences possible, especially in the case of multi-digital control signals. In the study [22], a circular buffer is proposed to equally distribute the switchings when multi-valve PWM and multi-valve PFM signals are used. The experimental results indicated that the maximum error is below 0.2 mm. However, the method caused pressure fluctuations and increased number of switchings because the multi-valve PWM or multi-valve PFM are constantly working.

In this paper, a novel position controller with switchings optimization is proposed to improve the position accuracy, while also reducing the total number of switchings and optimizing the switchings distribution among valves. First, to overcome the limitations of the model-based PNM (Pulse number modulation) controller caused by its minimum control flow rate, a differential PWM (DPWM) controller in which the duty cycles of the DPWM are determined by the position tracking error and the response time of the on/off valve is proposed to tune micro cross flow between the two DFCUs. Furthermore, the weight of the switching cost function is designed based on discrete flow rate analysis to reduce the total number of switchings of the DFCU under different pressure differences. In addition, a circular buffer and a circular switching schemes are proposed to equally distribute the switchings among all on/off valves in order to equalize the life time of the valves when the PNM and PWM signals are used, respectively. Finally, to validate the proposed control algorithm, a test platform is designed and experiments are carried out. The experimental results indicate that the proposed controller not only improves the positioning accuracy of a hydraulic cylinder but optimizes the number of switchings and the degree of equal distribution of switchings as well.

This paper is organized as follows: Working principle and mathematical model of the system are presented in Section II. Section III gives the design approaches of the model-based PNM controller and the differential PWM controller. Switching optimization is designed in Section IV. Comparative experimental results are obtained in Section V. Some conclusions are founded in Section VI.

2. Working Principle and Mathematical Model

In this research, an equal coded digital valve system is used as the study object as shown in Figure 1. According to the oil flow direction shown in Figure 1, it is easy to find that entrance throttle governing circuit (controlled by DFCU-PA) and out throttle governing circuit (controlled by DFCU-AT) work during the upward and downward movement of a hydraulic cylinder, respectively. So the velocity of the hydraulic cylinder is determined by the flow rate of the chamber A. In addition, DFCU-PA and DFCU-AT are used to control the oil inflow and oil outflow of the chamber A of hydraulic cylinder, respectively. Each DFCU is composed of eight on/off valves, which have almost the same flow coefficients. Moreover, the output discrete flow can be realized by coding the opening combination of eight on/off valves which is detailed in section 2.2.

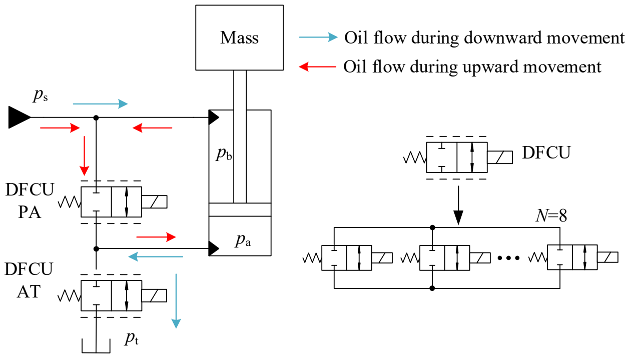


Figure 1. Schematic diagram of the system

2.1 Dynamical analysis of the DFCU

According to the above description, it can be understood that the control performance of the system is affected by the characteristics of the DFCU, including dynamic and static characteristics. The dynamic characteristics of the DFCU are directly determined by the opening and closing characteristics of the on/off valves. The relationship between voltage and the switching of the valve is used to assess the dynamic performance of the on/off valves, which is shown in Figure 2.

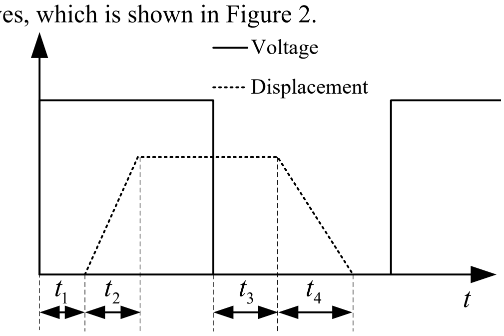


Figure 2. Switching characteristics of the on/off valves

As shown in Figure 2, the output displacement lags behind the voltage due to the influence of inductance and mechanical hysteresis [23]; however, this is not studied in this paper. In order to facilitate the modeling of the DFCU's dynamic characteristics, the opening delay time t_1, the opening movement time t_2, the closing delay time t_3 and the closing movement time t_4 are used to describe the on/off valve's dynamic characteristics.

2.2 Static analysis of the DFCU

The static performance of the DFCU determines the output flow range and control accuracy. The opening combination of the equal coded DFCU can be defined as

$$\boldsymbol{u}_{\text{int}} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \quad (1)$$

where "0" and "1" denote the open and closed states of the on/off valves, respectively. Assuming that the flow coefficient of each valve is same, the static flow rate of one valve can be expressed as

$$Q_1 = k_v \sqrt{\Delta p} \quad (2)$$

where k_v denotes the flow coefficient of one valve; Δp denotes the pressure difference of one valve. The discrete flow of the equal coded DFCU is shown in Figure 3.

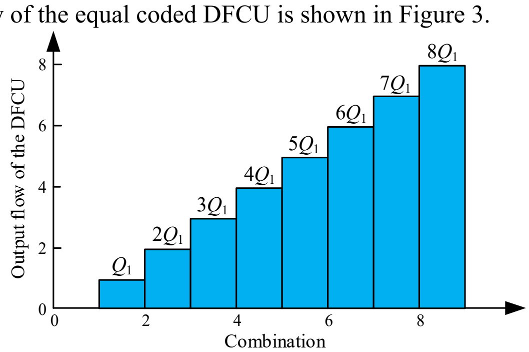


Figure 3. Output flow of the equal code DFCU

As shown in Figure 3, since all valves have the same flow coefficient, the number of flow combinations of the equal coded DFCU is N+1 (N being the number of the valves), which is relatively small compared with binary coded DFCU. However, the equal coded DFCU has high fault tolerance because the same output flow can be realized by different combinations.

3. Position controller

A model-based PNM controller and a DPWM controller are proposed for position control at high velocities and low velocities, respectively.

3.1 Model-based PNM controller

Nowadays, model-based PNM controller is the commonly used in digital valve systems. It includes a trajectory generation, a motion controller and a model-based valve controller as shown in Figure 4.

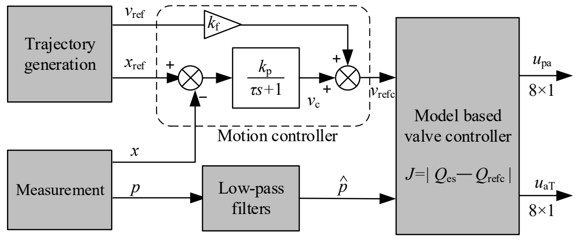


Figure 4. Schematic diagram of the model based PNM controller

As shown in Figure 4, the motion controller consists of a speed feedforward controller and a position closed-loop controller. The former is used to control the velocity of the system in open-loop and the latter is used to compensate for the remaining position error. Moreover, the controller has first order lag and feedforward from velocity which can be written as

$$\dot{v}_c = \frac{1}{\tau}\left(k_p\left(x_{\text{ref}} - x\right) - v_c\right) \quad (3)$$

$$v_{\text{refc}} = v_c + k_f v_{\text{ref}} \quad (4)$$

where v_c is the internal state variable of the controller; τ denotes the time constant of the filter; k_f and k_p denote the feedforward gain and closed-loop controller proportional gain, respectively; v_{ref} and x_{ref} denote the velocity and position reference, respectively. Actually, the discrete time controller is obtained by trapezoidal rule.

The flow rate reference (chamber A of hydraulic cylinder) can be defined as

$$Q_{\text{refc}} = A_a v_{\text{refc}} \quad (5)$$

where A_a denotes the effective area of the hydraulic cylinder chamber A. The estimated flow combination of the DFCU-PA can be written as

$$\boldsymbol{Q}_{\text{es}} = \boldsymbol{n}_{\text{int, pa}} k_{\text{ave}} \sqrt{\Delta \hat{p}} \quad (6)$$

$$\boldsymbol{n}_{\text{int, pa}} = \left[0, 1 \ldots N-1, N\right]^T \quad (7)$$

where k_{ave} denotes the average flow coefficient of the DFCU-PA (due to the difference of each valves' flow coefficient); $\Delta\hat{p}$ denotes the filtered pressure difference of the DFCU-PA; $\boldsymbol{n}_{\text{int, pa}}$ denotes the number of valves that open in different opening combinations of the DFCU-PA.

Therefore, the model-based controller is used to find the best combination in which error between Q_{refc} and $\boldsymbol{Q}_{\text{es}}$ is minimum. The cost function J can be written as

$$J = \min\left|Q_{\text{es}(i)} - Q_{\text{refc}}\right| \quad (8)$$

where $Q_{\text{es}(i)}$ denotes the value of column i of $\boldsymbol{Q}_{\text{es}}$ (the column of $\boldsymbol{Q}_{\text{es}}$ is N+1).

According to the equations (5), (6) and (8), when the v_{ref} and the position error are both small which likely make the Q_{refc} smaller than the flow rate of one valve, this can cause that no valve switches. In addition, the position error would remain unchanged. This is the drawback of the PNM control strategy in digital valve system.

3.2 Differential PWM controller

To solve the issue of the PNM control strategy of not being able to realize micro-positioning tasks at low-velocities (v<v_{min}), a differential PWM (DPWM) control strategy is proposed. Initially, the position of the cylinder is collected and transferred to the closed-loop controller. The duty cycles of the PWM signals calculated by the closed-loop controller are used to control the opening time differences between the two DFCUs. The cross flow of the two DFCUs is achieved and makes the hydraulic cylinder able to perform micro positioning tasks. The PWM signals of the two DFCUs are illustrated in Figure 5.

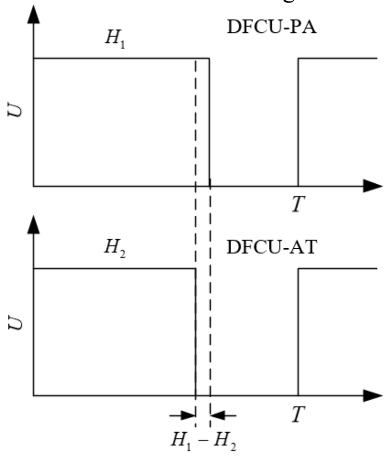


Figure 5. The PWM signals of the DFCUs

As shown in Figure 5, the duty cycles of the two PWM signals (DFCU-PA and DFCU-AT) are defined as

$$\begin{cases} \tau_1 = \dfrac{H_1}{T} \\ \tau_2 = \dfrac{H_2}{T} \end{cases} \tag{9}$$

where τ_1 and τ_2 denote the duty cycles of the two PWM signals, respectively. T denotes the period of the PWM signal. H_1 and H_2 denote the high voltage excitation time of the two PWM signals, respectively.

Considering that the on/off valve may not fully open under the PWM signal with a small duty cycle, the high voltage excitation time of the two PWM signals should be slightly greater than the response time of the on/off valve.

$$\begin{cases} H_1 \ge t_1 + t_2 \\ H_2 \ge t_1 + t_2 \end{cases} \tag{10}$$

The duty cycles of the two PWM signals can be written as

$$\begin{cases} \tau_1 - \tau_2 = k_{p1}\left|x_{ref} - x\right| \;, & \left|x_{ref} - x\right| \ge \Delta x_{min} \text{ and } x_{ref} \ge x \\ \tau_2 - \tau_1 = k_{p2}\left|x_{ref} - x\right| \;, & \left|x_{ref} - x\right| \ge \Delta x_{min} \text{ and } x_{ref} < x \\ \tau_1 = \tau_2 = 0 \;, & \left|x_{ref} - x\right| < \Delta x_{min} \end{cases} \tag{11}$$

where Δx_{min} denotes the minimum threshold position error of the DPWM control. k_{p1} and k_{p2} denote the controller gain of the DPWM during the upward and the downward movement of the hydraulic cylinder , respectively.

4. Switching optimization

4.1 Adaptive switching cost function

Actually, in some practical applications that require long life time, using PNM control can increase the total number of switchings and therefore leading to shorter life time of on/off valves. In order to make a compromise between control accuracy and total number of switchings, the following cost function is often used [16]:

$$J_1 = \left|Q_{es(i)} - Q_{refc}\right| + k_1 \sum_{i=1}^{N} \left|u_{i,new} - u_{i,cur}\right| \tag{12}$$

where $u_{i,new}$ and $u_{i,cur}$ denote the new opening state (0 or 1)and the current opening state (0 or 1) of the DFCU, respectively; k_1 denotes the weight of the switching cost function, which is used to find a compromise between accuracy and number of switchings.

In earlier publications [17, 22], k_1 is selected artificially through several simulations and experiments to obtain the optimal value. However, the selection of k_1 is affected by the pressure difference (different flow conditions) under which the DFCU operates. Assuming that

$$Q_{es(i)} \in \left[0,\ Q_{max}\right] \tag{13}$$

Then

$$\left|Q_{es(i)} - Q_{refc}\right| \le k_{ave}\sqrt{\Delta p} \tag{14}$$

where Q_{max} denotes the maximum flow rate of the DFCU; k_{ave} denotes the flow coefficient of the on/off valve.

Given that the maximum number of switchings required for the transition from the current opening state to the new opening state is N (transition from 0 to N), the following inequality equation can be obtained

$$k_1 \sum_{i=1}^{N} \left|u_{i,new} - u_{i,cur}\right| \le k_1 N \tag{15}$$

In order to obtain equal-weights for flow accuracy and the number of switchings, k_1 is defined as

$$k_1 = \frac{k_{ave}\sqrt{\Delta p}}{N} \tag{16}$$

As a result, k_1 adapts to pressure difference (Δp), flow coefficient (k_{ave}) and the number of valves per DFCU (N). The pressure difference often changes in different application, so the cost function is as follows

$$J_1 = \left|Q_{es(i)} - Q_{refc}\right| + \frac{k_{ave}\sqrt{\Delta p}}{N} \sum_{i=1}^{N} \left|u_{i,new} - u_{i,cur}\right| \tag{17}$$

In order to verify the effectiveness of the adaptive weight k_1 of the switching cost function, comparative experiments are implemented under different pressure differences. Each experiment is repeated 3 times to increase the reliability of the results. In the experiments, a fifth-order polynomial is used as reference trajectory, which is shown in Figure 6.

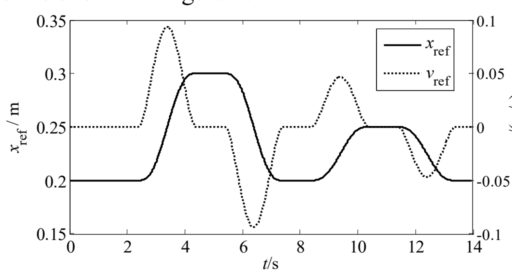
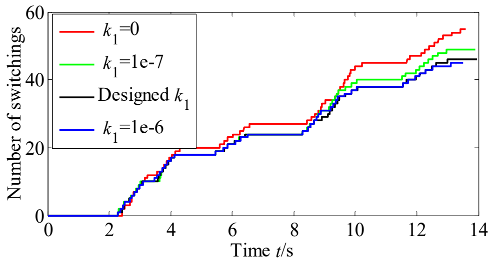
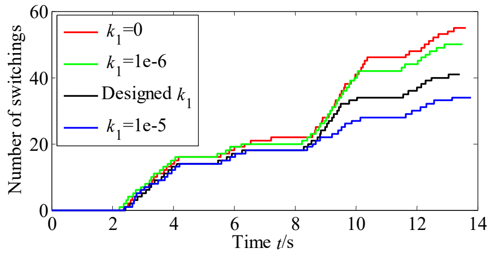


Figure 6. Reference trajectory

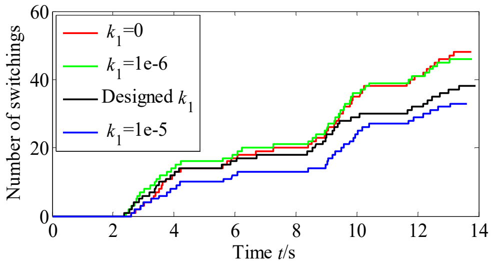
The total number of switchings of both DFCUs are shown in Figure 7.



(a) 1 MPa



(b) 2.5 MPa



(c) 4 MPa

Figure 7. Total number of switchings under different Δp

It can be seen from Figure 7 that, with the designed k_1, the total number of switchings of the DFCU can be controlled at a relatively low value under different pressure differences Δp. In addition to that, it can also be seen that when pressure difference Δp increases, the value of k_1 has to be increased to obtain a smaller number of switchings, on the contrary, the designed k_1 adapts to the change of the pressure difference which is used to obtain an optimal value.

Table 1 Performance indexes under different Δp

Different Δp	Different k_1	M_e	μ	σ
Δp =1 MPa	k_1=0	1.34	0.50	0.45
	k_1=1e-7	1.84	0.40	0.32
	Designed k_1	1.33	0.35	0.30
	k_1=1e-6	1.598	0.48	0.34
Δp=2.5 MPa	k_1=0	1.746	0.49	0.340
	k_1=1e-6	1.725	0.50	0.338
	Designed k_1	1.672	0.35	0.302
	k_1=1e-5	1.875	0.48	0.336
Δp=4 MPa	k_1=0	1.28	0.37	0.25
	k_1=1e-6	1.36	0.52	0.27
	Designed k_1	1.62	0.55	0.33
	k_1=1e-5	2.37	0.49	0.43

The maximum, average, and standard deviation of the tracking errors marked as M_e, μ, and σ are used to assess the position tracking performance with different k_1. The tracking performance indexes are presented in Table 1.

$$M_e = \max_{i=1,\dots,N}\{|e_1(i)|\} \tag{18}$$

$$\mu = \frac{1}{S_n}\sum_{i=1}^{S_n}|e_1(i)| \tag{19}$$

$$\sigma = \sqrt{\frac{1}{S_n}\sum_{i=1}^{S_n}\left[|e_1(i)|-\mu\right]^2} \tag{20}$$

As it can be seen from Table 1, with the designed k_1, the position tracking errors can be controlled at an optimal value which is close to the best value (k_1=0) and is less than the worst value.

4.2 Circular buffer for the PNM

When the DFCU is controlled by the PNM control strategy, the number of switchings is not equally distributed among all valves due to the characteristc of the PNM. In most cases, the first valve stays open while one of the other valves may keep switching. This phenomenon leads to a large difference in each valve's service life time.

In order to solve this problem, a circular buffer strategy is used to determine which valve to open [22], an example is illustrated in Figure 8. Where "green" indicates that the on/off valve is open and "gray" indicates that it is closed. "u_{PNM}" represents the number of the valve to open in DFCU-PA or DFCU-AT; T_s represents the sampling time of the control signal; the numbers 1 to 8 represent valves.As shown in Figure 8, u_{PNM} varies in different sampling times, the opening combination of on/off valves in the DFCU can be expressed as

$$\boldsymbol{i}_{\mathrm{PNM}} = \{i_L, i_{L+1}\dots i_{H-1}, i_H\} \tag{21}$$

where L and H denote the tail index and head index of the opening combination of on/off valves in the DFCU, respectively. For the circular buffer, if u_{PNM} increases, L remains unchanged and H increases; on the contrary, if u_{PNM} decreases, H remains unchanged and L increases.

With the circular buffer, the number of switchings can be equally distributed to each valve under the PNM control. The L and H can be calculated as

$$L_{\mathrm{new}} = \begin{cases} L_{\mathrm{cur}} & u_{\mathrm{PNM,\,new}} \ge u_{\mathrm{PNM,\,cur}} \\ L_{\mathrm{cur}} + u_{\mathrm{PNM,\,new}} - u_{\mathrm{PNM,\,cur}} & u_{\mathrm{PNM,\,new}} < u_{\mathrm{PNM,\,cur}} \end{cases} \tag{22}$$

$$H_{\mathrm{new}} = \begin{cases} H_{\mathrm{cur}} + u_{\mathrm{PNM,\,new}} - u_{\mathrm{PNM,\,cur}} & u_{\mathrm{PNM,\,new}} \ge u_{\mathrm{PNM,\,cur}} \\ H_{\mathrm{cur}} & u_{\mathrm{PNM,\,new}} < u_{\mathrm{PNM,\,cur}} \end{cases} \tag{23}$$

where L_{cur} and H_{cur} denote the tail index and head index of the current state opening combination of on/off valves in the DFCU, respectively; L_{new} and H_{new} denote the tail index and head index of the new state opening combination of on/off valves in the DFCU, respectively.

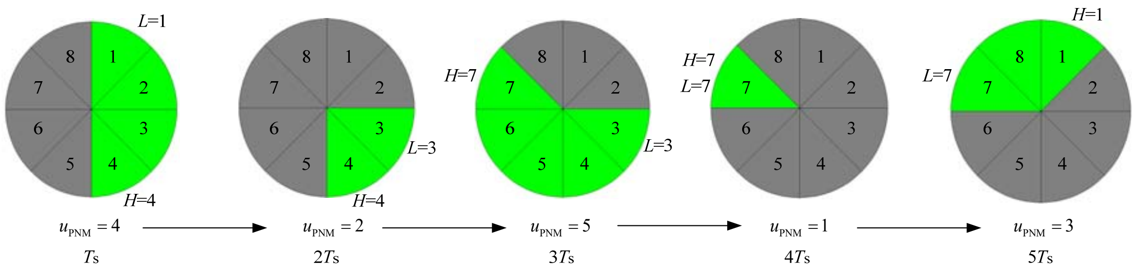


Figure 8. Working principle of a circular buffer with eight valves under the PNM control

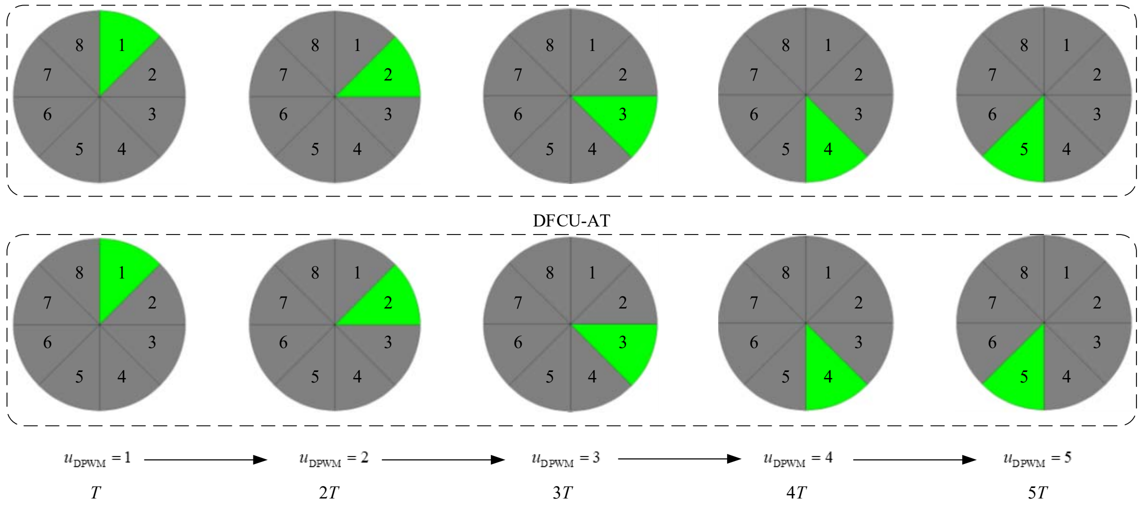


Figure 9. Working principle of circular switching with eight valves under the DPWM control

4.3 Circular switching for the DPWM

The DPWM controller can improve the positioning accuracy but causing a larger number of switchings. For example, the number of switchings of one valve can reach 40 per second if it is controlled by a PWM signal which results in fatigue wear and deterioration of valve port characteristics. Therefore, in order to equally distribute the life time of all valves, the pulse generation of PWM signal needs each on/off valve to participate equally. A circular switching strategy is proposed to solve this problem. The working principle is illustrated in Figure 9, where "u_{PWM}" indicates which valve to open in DFCU-PA and DFCU-AT at the same time; T represents the period of the DPWM signal, and the rest is the same as Figure 8.

It can be seen from Figure 9, only one on/off valve in DFCU-PA and DFCU-AT can open at a time (during period T), which is different from the PNM controller. So, the circular buffer is useless to for DPWM controller. u_{PWM} increases step by step with the increasing of pulse number. The pulse generation of the PWM signal is presented in Figure 10.

As shown in Figure 10, the PWM signal of the DFCU consists of the pulses of eight on/off valves. A cycle consists of eight pulses, for example, the first pulse is used for control valve 1, and the second pulse is used for control valve 2, and so on. The frequency of each valve's pulse is $f/8$ (f is the frequency of the DFCU's PWM signal). Therefore, the total pulses are equally distributed to eight valves and the service life time of each valve can be equally distributed.

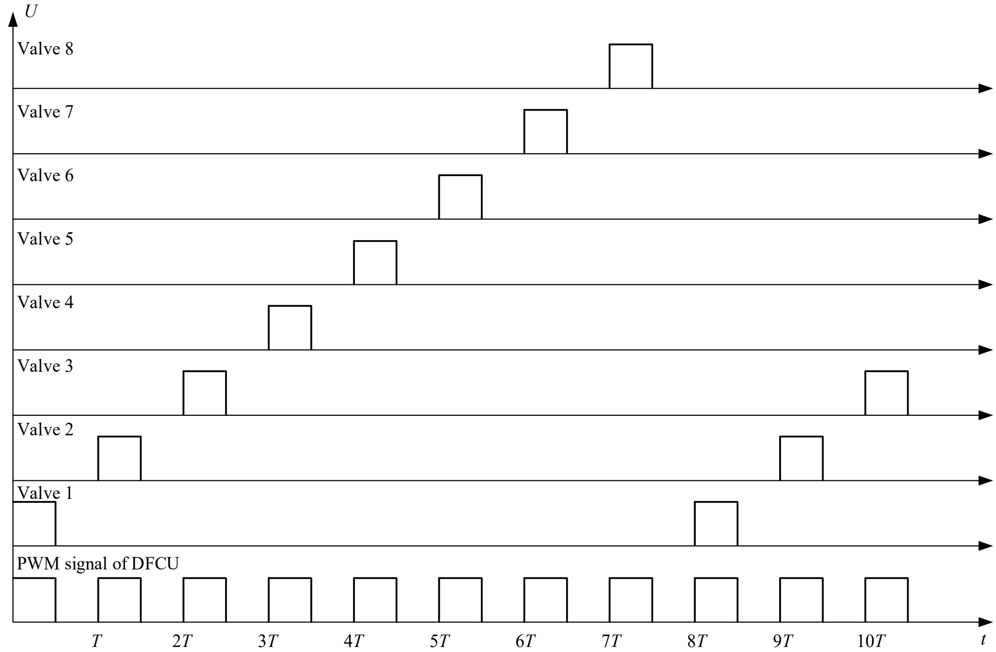


Figure 10. Pulse generation of the PWM signal

5 Comparative experimental results

To verify the effectiveness of the proposed design, comprehensive performance comparisons are conducted on a hydraulic test platform, which is set-up as shown in Figure 11. The platform mainly consists of a vertical hydraulic bench which contains an asymmetric cylinder (A_a= 804mm^2, A_b=550mm^2 and the stroke is 400 mm), a linear encoder (Heidenhain LS477, resolution: 0.5 μm) to generate the position and velocity information, three pressure sensors (Trafag NAH, pressure range: 25 MPa) to measure p_s, p_t and p_a, an equal coded valve system consisting of DFCU-PA and DFCU-AT, a mass load m=50 Kg, a hydraulic supply of 8 MPa, and a measurement and real-time control system.

Each DFCU prototype consists of eight on/off valves which are driven by an AC booster power electronic circuit presented in [24]. The circuit provides high current peak to open a valve by using 220 uF boost capacitor and low holding voltage to maintain the valve open. The average flow coefficients of the two DFCUs are 10.2×10^{-9} $\mathrm{m^3/s\sqrt{Pa}}$ and 11.9×10^{-9} $\mathrm{m^3/s\sqrt{Pa}}$, respectively. The measurement and real-time control system is conducted in dSPACE 1202 board control system. The monitor software is programmed with dSPACE control desk. To implement these controllers described above, MATLAB/Simulink model needs to be compiled into the discretization C++ codes. The measurement sampling time and the PWM pulse generation sampling time are 1 ms, whereas the sampling time of control signal is 5 ms, which is slightly bigger than the response time of the valves.

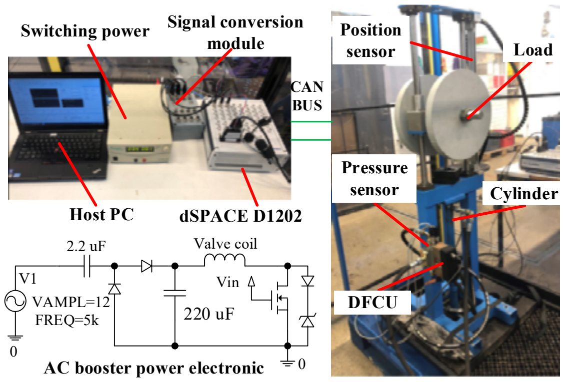


Figure 11. Experimental platform of the digital valve system

To verify the effectiveness of the proposed control scheme, the following five controllers are compared.

1) Controller 1: This is the traditional model-based PNM controller with position feedback and velocity feedforward. The position feedback controller gain tuned carefully is k_p=20 and the velocity feedforward gain k_v is chosen as 1 based on the open loop identification.

2) Controller 2: This controller is same as controller 1 but with the proposed adaptive cost switching weight as described in section 3.1.

3) Controller 3: This controller is same as controller 2 but with the proposed circular buffer, which is used to equally distribute the number of switchings among all on/off valves when the PNM control is used.

4) Controller 4: This controller is same as controller 3 but with one valve controlled by the proposed DPWM, which is used to improve the positioning accuracy in case (v< v_{min} and |Δx|>Δx_{min}). The DPWM controller gains tuned carefully are k_{p1}=1500, k_{p2}=1200. The frequency of PWM

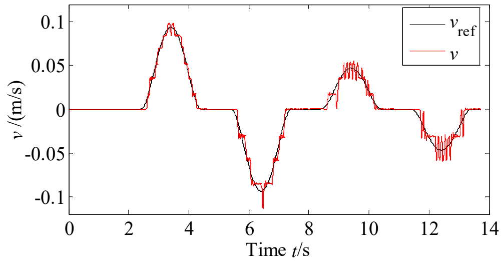
(f) is 20 Hz. The v_{min} and Δx_{min} tuned carefully are 0.005 m/s and 20 μm.

5) Controller 5: This is the final controller. It is same as controller 4 but with the proposed circular switching, which is used to equally distribute the number of switchings of on/off valves when the DPWM control stategy is adopted.

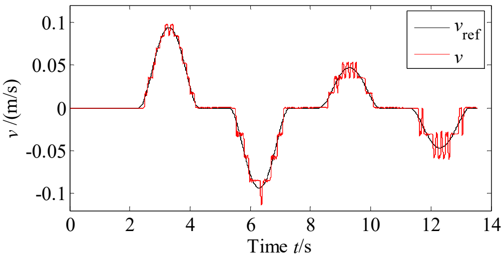
The performance of the five controllers when tracking a trajectory are tested. Similar to previous study [22], the reference trajectory shown in Figure 6 is used. Each experiment is repeated 3 times to increase the reliability of the results.

5.1 Tracking performance

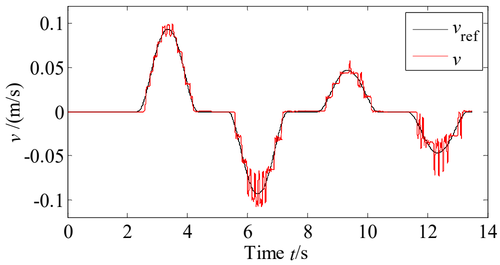
In order to compare the five controllers, the velocity and position are used to assess the tracking performance. The velocity can reflect the switching of the DFCU.



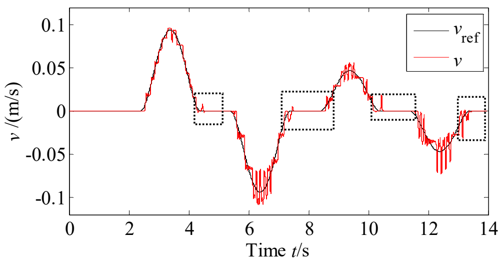
(a) Controller 1



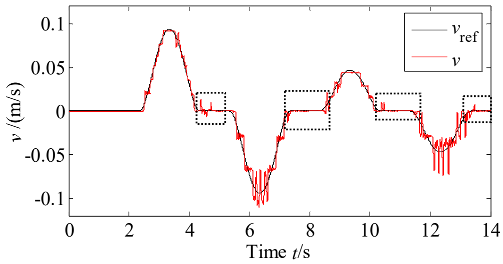
(b) Controller 2



(c) Controller 3



(d) Controller 4

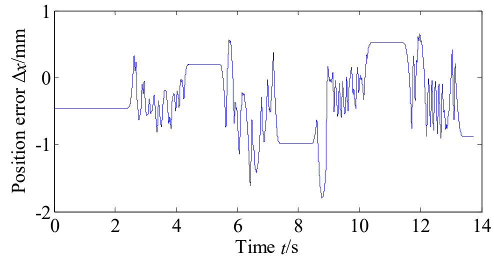


(e) Controller 5

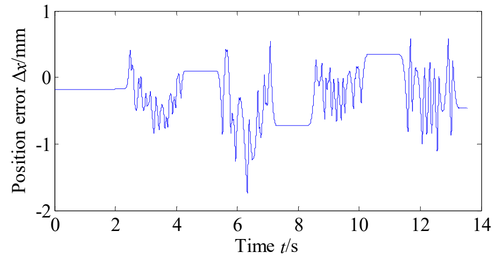
Figure12. Compared tracking velocity

As shown in Figure 12 (a), (b) and (c), the step-wise increase of the velocity occurs with the increase of the reference velocity due to the PNM coding. Comparing controller 1 and 2, the adaptive switching cost function almost has no effect on the velocity. But as shown in Figure 12 (c), the circular buffer slightly increases the velocity fluctuation, especially at the high velocities because more valves are involved in the flow control. Moreover, when using DPWM, there are more fluctuations that occur as shown with the dotted boxes in Figure 12 (d) and (e); however, the fluctuations are acceptable since they are relatively small compared to the ones that occur at high velocities.

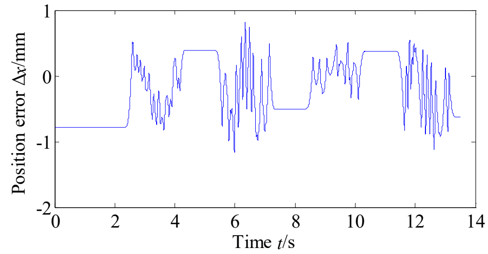
Tracking position errors of the five controllers are shown in Figure 13.



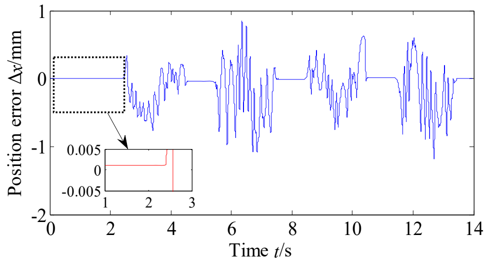
(a) Controller 1



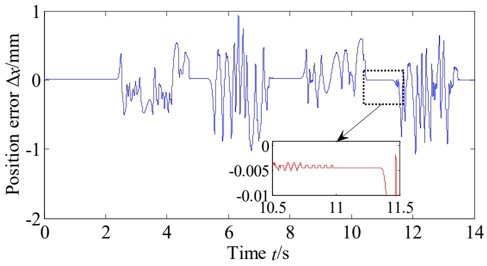
(b) Controller 2



(c) Controller 3



(d) Controller 4



(e) Controller 5

Figure 13. Tracking position errors

As it can be seen in Figure 13 (a), (b) and (c), when the PNM is used, the average positioning error and the minimum positioning error almost reach 300 μm and 100 μm, respectively. This is because when $v<v_{min}$, the calculated Q_{refc} is less than the output flow of one valve which results in the output of the PNM being 0. Comparing controller 1, 2 and 3, it can be seen that the proposed adaptive switching cost function and the circular buffer almost have no effect on the position accuracy. When using the DPWM (Figure 13 (d)), the average positioning error (10 μm) and the minimum positioning error (1 μm) are reduced by 96.7% and 98%, respectively, compared to when PNM is used. This clearly shows that the proposed DPWM controller can improve the positioning accuracy. Comparing controller 4 and 5, it can also be noticed that the circular switching method almost has no effect on the positioning accuracy; as previously explained, the aim of the circular switching method is to equally distribute the number of switchings among the valves, not to simultaneously affect the positioning accuracy.

The average and standard deviation of the tracking position errors are used to assess the performance of each control algorithm as shown in Table 2.

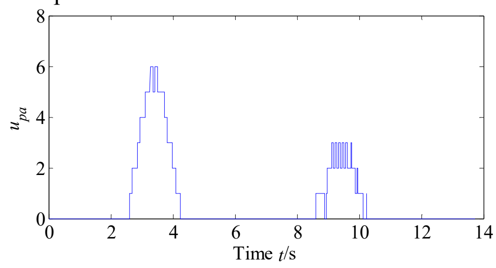
Table 2. Performance indexes of the five controllers

	μ	σ
Controller 1	0.50	0.33
Controller 2	0.35	0.27
Controller 3	0.44	0.25
Controller 4	0.19	0.24
Controller 5	0.17	0.21

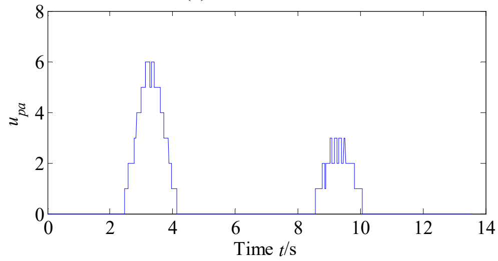
As shown in Table 2, the performance of controller 4 and 5 are better than controller 1, 2 and 3. For instance, compared to controller 1, the average and standard deviation of the position tracking errors are reduced by 66% and 36%, respectively, with the use of controller 5.

5.2 Switching optimization results

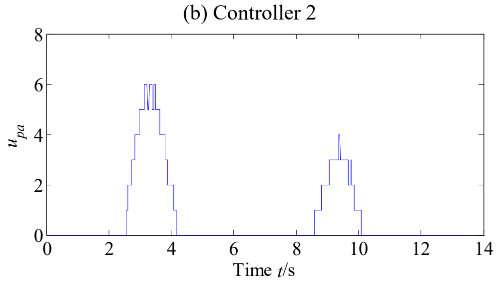
In order to analyze the switching performance of the five controllers, the switching state and the number of switchings are used to assess the performance. The switching state of the DFCU-PA can be observed in Figure 14. Where "u_{pa}" represents the number of on/off valves to open in the DFCU-PA.



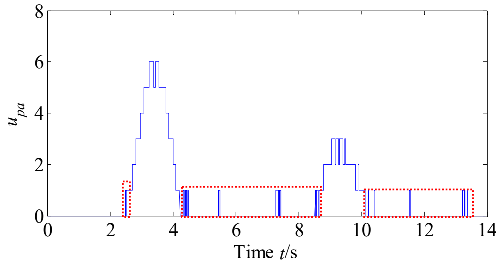
(a) Controller 1



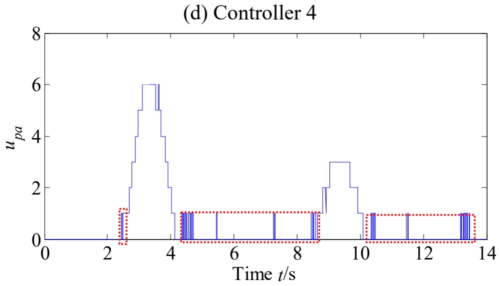
(b) Controller 2



(c) Controller 3



(d) Controller 4



(e) Controller 5

Figure.14 Switching state of the DFCU-PA

Table 3. Optimization results of each valve's number of switchings in DFCU-PA

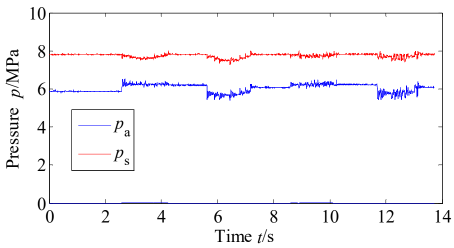
	Controller 1	Controller 2	Controller 3	Controller 4	Controller 5
Valve 1	10	6	4	67	10
Valve 2	6	6	2	4	10
Valve 3	14	10	2	4	16
Valve 4	2	2	4	4	10
Valve 5	2	2	4	4	16
Valve 6	4	4	6	6	18
Valve 7	0	0	4	4	10
Valve 8	0	0	4	4	11
Total number of switchings	38	30	30	97	101
Standard deviation	4.7	3.2	1.2	20.8	3.2

Figure 14 (a), (b) and (c) depict the switchings of the DFCU-PA under the PNM. These switchings can only occur when the velocity is higher than v_{min}. Additionally, Figure 14 (d) and (e) clearly show the working states of the DPWM's pulses which work only near the start and end of the PNM signal. Only several pulses of the DPWM are needed to make the position error lower than the Δx_{min}.

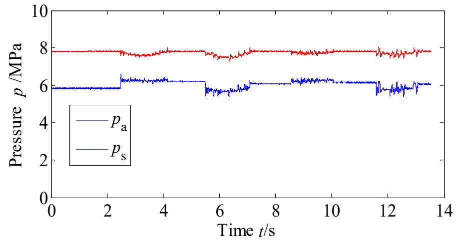
The number of switchings of the each on/off valve is presented in Table 3. Standard deviation is used to assess the dispersion of each valve's number of switchings. The smaller the standard deviation is, the smaller is the difference of the number of switchings across the valves. Compared to controller 1, controller 2 reduces the total number of switchings of DFCU-PA by 21% due to the adaptive switching cost function. For controller 3, which utilizes the circular buffer, the total number of switchings remains the same as controller 2 but the standard deviation is reduced by 62.5%. When controller 4 is used, the standard deviation drastically increases from 1.2 to 20.8, compared to controller 3, due to the fact that only one valve is controlled by the DPWM signal. For controller 5, which utilizes the circular switching method, the standard deviation is reduced by 85%, compared to controller 4, which reflects that controller 5 improves the degree of equal distribution of switchings among the valves.

5.3 Pressure fluctuation analysis

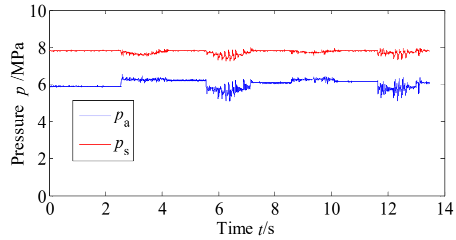
Pressure fluctuation is a critical problem in digital valve controlled systems. In order to analyze the pressure fluctuation with the five controllers, the supply pressure (p_s) and pressure of chamber A (p_a) are observed as shown in Figure 15.



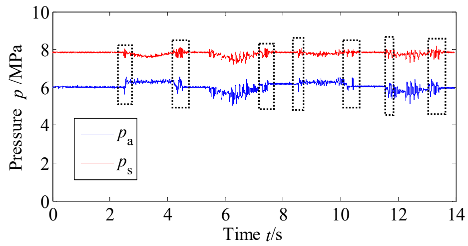
(a) Controller 1



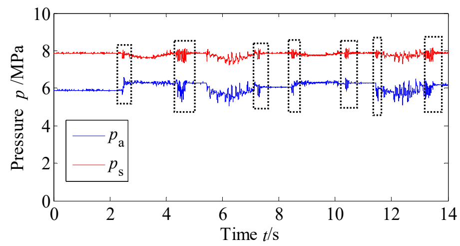
(b) Controller 2



(c) Controller 3



(d) Controller 4



(e) Controller 5

Figure.15 Pressure fluctuation

It can be seen from Figure 15 (a) and (b), the pressure fluctuation with controller 2 is almost the same as controller 1, which indicates that the adaptive switching cost function has no effect on the pressure fluctuation. Additionally, compared to controller 1 and 2, controller 3 slightly increases pressure fluctuation, as observed in Figure 15 (c). This is due to the flow disturbance caused by the circular buffer in which more valves are involved in and each valve's dynamic characteristic is slightly different.

When using controller 4, there are more pressure fluctuations that occur as shown with the dotted boxes in Figure 15 (d). Additionally, the circular switching method, which is used in controller 5, also has slight effect on the pressure fluctuation due to uncertainty between different response times of the valves; however, they are acceptable since they are relatively small as shown in Figure 15 (e).

6. Conclusions

In this study, a new position controller with switching optimization for an equal coded digital valve system is proposed, and its working principle is presented. The position controller consists of a model-based PNM and a DPWM controller. The switching optimization consists of an adaptive switching cost function, a circular buffer for the PNM and a circular switching method for the DPWM.

Extensive comparative experiments have been carried out to illustrate the effectiveness of the proposed schemes.

(1) The average positioning error and the minimum positioning error are only 10 μm and 1 μm, respectively, when the proposed DPWM control strategy is used. The experimental results indicate that the proposed controller can significantly improve the positioning accuracy of the hydraulic cylinder, compared to the model-based PNM controller, In addition to that, the pressure fluctuation caused by the proposed controller is slight and acceptable, since DPWM pulses only work occasionally.

(2) An adaptive weight of the switching cost function is proposed for the first time. The design criterion is presented and experimentally validated. It can be found that the proposed adaptive weight of the switching cost function reduces the total number of switchings by 21% without affecting the positioning accuracy, compared to when no weight are used.

(3) A circular buffer for the PNM is used to equally distribute the number of switchings among the valves. The experimental results indicate that the circular buffer reduces the standard deviation of the number of switchings by 62.5%, compared to without. To further improve the degree of equal distribution of the switchings when the DPWM signal is used, a new circular switching method is proposed and the results indicate that the standard deviation of the number of switchings is reduced by 85% compared to the circular buffer. In addition, the effect of both methods on the pressure fluctuations is analysed and results showed that the fluctuations remain acceptable.

References

1. Wu S, Zhao XY, Li CF, et al. Multi-objective optimization of a hollow plunger type solenoid for high speed on/off valve. *IEEE Transactions on Industrial Electronics*, 2018, 65(4): 3115-3124.

2. Yang HY, Wang S, Zhang B, et al. Development and prospect of digital hydraulic valve and valve control system. *Journal of Jilin University (Engineering and Technology Edition)*, 2016, 46(5): 1494-1505.

3. Yang HY, Pan M. Engineering research in fluid power: a review. *Journal of Zhejiang University Science A*, 2015, 16(6): 427-442.

4. Linjama M, Laamanen A, Vilenius M. Is it time for digital hydraulics. *The Eighth Scandinavian International Conference on Fluid Power*. 2003.

5. Scheidl R, Linjama M, Schmidt S. Is the future of fluid power digital. *Proceedings of the Institution of Mechanical Engineers Part I Journal of Systems & Control Engineering*, 2012, 226(6):721-723.

6. Pan M, Plummer A. Digital switched hydraulics. *Frontiers of Mechanical Engineering*, 2018, 13(2):225-231.

7. Brandstetter R, Deubel T, Scheidl R, et al. Digital hydraulics and "Industrie 4.0". *Proceedings of the Institution of Mechanical Engineers Part I Journal of Systems & Control Engineering*, 2017, 231(2): 82-93.

8. Wang F, Gu L, Chen Y. A continuously variable hydraulic pressure converter based on high-speed on-off valves. *Mechatronics*, 2011, 21(8): 1298-1308.

9. Wang F, Gu L, Chen Y. A hydraulic pressure-boost system based on high-speed on-off valves. *IEEE/ASME transactions on mechatronics*, 2013, 18(2): 733-743.

10. Kogler H, Scheidl R. Two basic concepts of hydraulic switching converters. *First Workshop on Digital Fluid Power*, Tampere, Finland. 2008.

11. Zhao J, Yue P, Grekhov L, et al. Hold current effects on the power losses of high-speed solenoid valve for common rail injector. *Applied Thermal Engineering*, 2018, 128: 1579-1587

12. Laamanen A, Siivonen L, Linjama M, et al. Digital flow control unit-an alternative for a proportional valve? In: *Bath Workshop on Power Transmission and Motion Control* (PTMC 2004). 2004. p. 297-308.

13. Linjama M, Tammisto J. New Alternative for Digital Pump-Motor-Transformer. *The Second Workshop on Digital Fluid Power*, November 12-13, 2009, Linz, Austria, pp. 49–61.

14. Heikkilä M, Linjama M. Displacement control of a mobile crane using a digital hydraulic power management system. *Mechatronics*, 2013, 23(4): 452-461.

15. Linjama M, Huova M, Pietola M, et al. Hydraulic hybrid actuator: theoretical aspects and solution alternatives. *The Fourteenth Scandinavian International Conference on Fluid Power*, May 20-22, 2015.

16. Linjama M, Koskinen K T, Vilenius M. Accurate trajectory tracking control of water hydraulic cylinder with non-ideal on/off valves. *International Journal of Fluid Power*, 2003, 4(1): 7-16.

17. Linjama M, Vilenius M. Improved digital hydraulic tracking control of water hydraulic cylinder drive. *International Journal of Fluid Power*, 2005, 6(1): 29-39.

18. Wu J, Wang S, Wang J, et al. A compound control strategy

for the digital valve based hydraulic position tracking system. *Proceedings of the 33rd Chinese Control Conference.* IEEE, 2014: 7869-7873.
19. Long G, Lumkes Jr J. Comparative study of position control with 2-way and 3-way on/off electrohydraulic valves. *International journal of fluid power*, 2010, 11(1): 21-32.
20. Huova M, Plöckinger A. Improving resolution of digital hydraulic valve system by utilizing fast switching valves. *Proceedings of the Third Workshop on Digital Fluid Power*. October 13-14 2010, Tampere, Finland, 2010: 79-92.
21.Huova M, Linjama M, Siivonen L, et al. Novel Fine Positioning Method for Hydraulic Drives Utilizing On/Off Valves. *BATH/ASME 2018 Symposium on Fluid Power and Motion Control. American Society of Mechanical Engineers*, 2018: V001T01A046-V001T01A046.
22. Paloniitty M, Linjama M. High-linear digital hydraulic valve control by an equal coded valve system and novel switching schemes. *Proceedings of the Institution of Mechanical Engineers Part I Journal of Systems & Control Engineering*, 2018, 232(3): 258-269.
23. Zhang B, Zhong Q, Ma J, et al. Self-correcting PWM control for dynamic performance preservation in high speed on/off valve. *Mechatronics*, 2018, 55: 141-150.
24. Linjama M, Paloniitty M, Tiainen L, et al. Mechatronic design of digital hydraulic micro valve package. *Procedia engineering*, 2015, 106: 97-107.

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