doi:10.3772/j.issn.1006-6748.2018.03.011

Control characteristics of D + A combined multi-pump controlled system①

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Abstract

In order to solve the flow mismatch problem between pumping source output and workload demand, a novel configuration of D + A combined multi-pump controlled hydraulic system, similar to a pump-controlled system, is proposed for a large power hydraulic system in this study. This novel configuration consists of several parallel fixed displacement pumps of different sizes and proportional variable displacement pumps, which is controlled by digital signal (on/off) and analog signal respectively (D + A pumps). The system flow is divided into two parts, one is the total flow from fixed displacement pumps, and the other is the rest desired flow supplied by variable displacement pumps to smooth and improve the demand flow. First, basic design principles and evaluation indicators of the proposed system are introduced. Then, a flow state matrix of the binary-coding digital pumps (1:2:4) is obtained to provide the control signals of pumps. Experimental results show that the system output flow tracks well with acceptable flow deviation, though a little lag behind input signal.

Key words: multi-pump, design principles, flow state matrix, evaluation indicator, energy saving

0 Introduction

Energy consumption in hydraulic industry has been attracting great concern due to the issue of energy crisis today. Mobile machines consume considerable amounts of fuel during their operating lifetime, which is accompanied by high CO_2 emissions. Recent demands on improved system efficiency and reduced system emissions have driven improvements in hydraulic system architectures as well as system supervisory control strategies employed in large flow and heavy machinery. However, the effect of just improving the hydraulics efficiency has either a minor influence on the machine fuel consumption. The problem of achieving maximal system efficiency in large flow and heavy machinery is still a great challenge. To address these problems mentioned above, some novel approaches are required urgently.

For these high power hydraulic equipments, displacement controlled (DC) hydraulic pumps can operate hydraulic cylinders directly, and eliminate the throttling losses occurring in load-sensitive or other valve controlled systems[1,2]. One obstacle for the introduction of DC actuation to the market is the increased machine production costs due to the one-pump-per-actuator requirement. The combination of displacement control and pump switching architecture represents a valuable alternative for high efficiency and cost effective hydraulic systems[3,4]. Digital hydraulics is a new alternative, offering a wide range of innovative solutions[5-7], such as pulse width modulated system (PWM) and pulse code modulated (PCM). During the past years, digital valve concept was investigated in Refs[8-10], where proportional valves were replaced by several simple switching valves in parallel contributing to reducing throttling losses. PCM with several pumps operating continuously in parallel can realize output flow of the different requirements[11-13]. Generally, digital pumps in parallel consist of a number of fixed displacement pumps, with different coding methods to ensure each pump size, such as binary coding method, etc. Heitzig and Theissen combined different size pumps with binary, ternary or other coding meth-

① Supported by the National Natural Science Foundation of China (No. 51575471) and the Key Project of Natural Science Foundation of Hebei Province (No. E2016203264).

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Received on July 6, 2017

ods to output their individual flows in a stepwise, utilizing several simple on/off valves in parallel, but with almost continuous characteristics[14,15]. Another way to implement digital pump is to control each piston independently by active on/off valves. The shared use of one digital pump for several actuators in a velocity control circuit is a promising concept to improve energy efficiency, comparing separate analog and digital pumps for each actuator[16]. This type of systems was proved well, but the flow step leading to pressure peak and oscillations still exists.

In order to make it possible for PCM flow to supply continuously, variable displacement pumps with analog control (simplified as analog pumps) are combined with fixed displacement pumps with digital control (simplified as digital pumps) to smooth the flow supply curve in this study, which is called the D + A combined multi-pump controlled system, where composition, flow division and evaluating indicators are investigated. Furthermore, the flow state matrix is found and solved to get the control method. To validate the feasibility and the fundamental flow characteristics of D + A combined multi-pump controlled system, a test bench is established and experiments have been conducted.

1 Configuration of D + A combined multi-pump controlled system

1.1 Composition of D + A combined multi-pump controlled system

The schematic of proposed D + A combined multi-pump controlled system is shown in Fig. 1, which consists of m fixed displacement pumps and n variable displacement pumps, usually of different sizes, working in parallel. The value of m and n is determined by the flow requirements, flow division method and evaluation indicators. Each pump has a safety valve S_i, but each digital pump has one more on/off valve DV_i. To protect each pump, the check valve CV_i is assigned behind each pump. According to the actuator velocity, the total flow is adjusted by control on/off valves of digital pumps and displacement of analog pumps. And the direction of the actuator is changed by the 3-way-4-port directional valve.

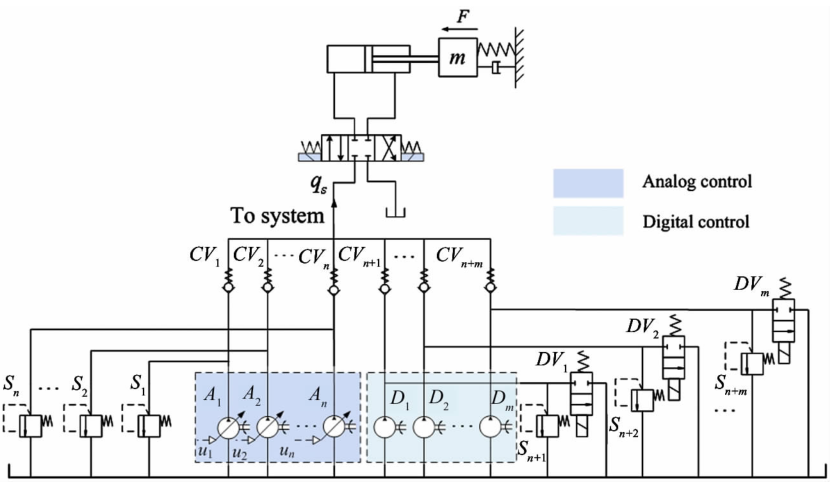


Fig. 1 Configuration schematic of D + A combined multi-pump controlled system

1.2 Flow division of D + A combined multi-pump controlled system

Assuming that an actuator flow requirement curve is shown in Fig. 2(a), the surrounding area of the curve can be divided arbitrarily by a grid regional division method. Obviously, it can be regarded as two area regions, one is the maximal area of flow steps curve that is proximate to the flow requirement curve (see Fig. 2(b)), and the other is the rest area between flow requirement curve and maximal flow steps curve (see Fig. 2(c)). The maximal flow step curve can be formed through different size and amount of digital pumps combinations. According to the area deviation from Fig. 2(c), different analog pumps are combined to realize the irregular flow output curve and provide the rest desired flow to smooth and the demand flow accurately.

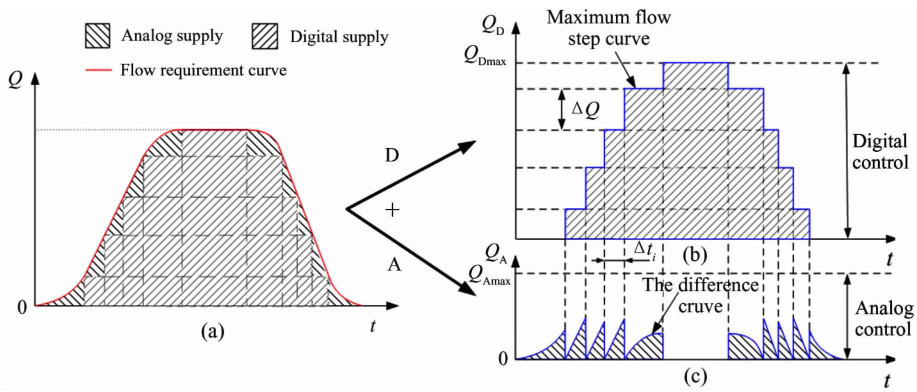


Fig. 2 Division of a certain flow requirement

Due to different sizes of grid regional division, there are different combination methods of digital pumps and analog pumps. The smaller the flow interval division is, the higher the switching frequency would be. It would cause more switching impact and require fast response of analog pumps. Vice versa, the greater flow interval division, though the switching times reduce, the greater output flow of analog pumps, and the number of analog pump would increase. Thus, a reasonable flow gradation difference ΔQ must be selected to meet the flow requirements according to switching impact, switching frequency and number of pumps.

For digital pumps displacement size specification, the common coding methods can be referenced, such as binary and ternary. However, there are still many factors influencing selection of digital pumps and analog pumps, such as pumps flow deviation, cost, switching impact and so on.

1.3 Evaluation indicators of D + A combined multi-pump controlled system

In order to evaluate the characteristics of different D + A multi-pump combinations, the pumps flow deviation, cost, and switching impact would be as evaluation indicators.

1) Pumps flow deviation

The definition of the flow deviation refers to the deviation between the input flow requirements of actuators and the output flow of the multi-pump source under open loop control:

$$\triangle q_t = q_{\text{out}} - q_{\text{need}} \tag{1}$$

where, $\triangle q_t$ is the flow deviation of pumps (L/min), q_{out} is the output flow of pumps (L/min), q_{need} is the need flow of actuator (L/min).

In order to reflect the indicator exactly and avoid offset of positive error and negative error, the square of the difference between the given value and the input value at each moment is integrated in a typical working cycle T. Normalize the flow deviation,

$$\varepsilon^1 = \frac{\int_0^T [q_{\text{out}}(t) - q_{\text{need}}(t)]^2 \mathrm{d}t}{T \cdot [q_{\text{out}}(t) - q_{\text{need}}(t)]^2_{\max}} \tag{2}$$

Flow deviation ε^1 is a value ($0 \leqslant \varepsilon^1 \leqslant 1$) and it increases with the value of the flow deviation increasing. As a result, the degree of flow deviation could evaluate the output flow control accuracy of the D + A combined multi-pump source under open loop control.

2) Cost of multi-pump

The cost is one of the important indicators to evaluate the D + A combined multi-pump controlled hydraulic system. The main cost depends on the number of digital pump m and analog pump n, and displacement size D. Normalize the total cost:

$$N^1 = \frac{\sum_{i=1}^{m} a_i D_i + \sum_{j=1}^{n} b_j \gamma_j}{\max\{a_i D_i\} \cdot m + \max\{b_j \gamma_j\} \cdot n} \tag{3}$$

where, m is the number of fixed displacement pumps, n is the number of variable displacement pumps, D_i is displacement size of the ith digital pump (mL/r), γ_j is the displacement size of the jth analog pump (mL/r), a_i is the price of the ith digital pump (Yuan), b_j is the price of the jth analog pump (Yuan).

3) Flow switching impact of multi-pump

Due to the different displacement setting rules of digital pumps, the multi-pump source flow switching impact value is determined by the maximum displacement and switching frequency of digital pump, and it has important influence on control characteristics and lifetime.

The pumps maximum switching impact value depends on the ratio of maximum displacement of digital pump to the total displacement of all digital pumps.

$$\sigma_{\max} = \frac{D_{\max}}{D_{\text{total}}} \tag{4}$$

where, $D_{\max}$ is the maximum displacement of digital pumps (L/min), D_{total} is the total displacement of all digital pumps (L/min), $\sigma_{\max}$ is the Maximum switching impact degree.

However, the pumps average switching impact value σ_{average} depends on the switching impact $\frac{D_i}{D_{total}}$ and use probability $\frac{f_i}{f}$ of each digital pump. The switching frequency f is defined as the state change times per second of all digital pumps by on/off valves switching on and off from the minimum flow to maximum flow.

$$\sigma_{\text{average}} = \sum \frac{f_i}{f} \cdot \frac{D_i}{D_{\text{tatal}}} \quad (5)$$

For instance, the displacements of digital pumps are in ratio of 1:2:4. The minimum flow output gradation (flow resolution Q) of flow gradation is 1/7 and the control signal of digital pumps is uniquely determined whatever flow gradation output is, as shown in Table 1.

According to Eq. (4), the average switching impact value,

$$\sigma_{124} = \left(\frac{4+3}{11} \times \frac{1}{7} + \frac{2+1}{11} \times \frac{2}{7} + \frac{1+0}{11} \times \frac{4}{7}\right) \times 100\% = 22.0\% \quad (6)$$

And so on, the switching impact of different displacement ratios of 1:1:1, 1:2:3 and 1:2:4 could be compared by Eq. (4). Assume that the three kinds of combination of digital pumps have the same maximum output flow capacities, and the displacement value and flow gradation are uniquely determined. The results are shown in Table 2.

Table 1 Switching frequency of digital pumps with binary displacement ratio 1:2:4

Flow	$2^0 \cdot D_1$	$2^1 \cdot D_1$	$2^2 \cdot D_1$	Switching frequency in sequence
$1Q$	●	○	○	1
$2Q$	○	●	○	2
$3Q$	●	●	○	1
$4Q$	○	○	●	3
$5Q$	●	○	●	1
$6Q$	○	●	●	2
$7Q$	●	●	●	1
sum	4 + 3	2 + 1	1 + 0	11

Note: ● switch on, ○switch off.

From Table 2, it shows that the least switching times and the greatest impact is displacement ratio 1:1:1; the highest switching frequency and the least impact is displacement ratio 1:2:4. The switching frequency of multi-pump source depends on displacement ratios of digital pumps. It can be concluded that the average switching impact value is related to switching frequency.

Table 2 Comparison of digital pumps switching impact

Ratio	Flow	Flow gradation	Switching times	Average impact
1:1:1	14, 14, 14	14/28/42	3	33.3%
1:2:3	7, 14, 21	7/14/21/28/35/42	9	25.9%
1:2:4	6, 12, 24	6/12/18/24/30/36/42	11	22%

2 Flow state matrix with binary displacement

Assume that the output flow $Q(t)$ of D + A combined multi-pump controlled system could be expressed as

$$\boldsymbol{Q}(t) = \boldsymbol{B} \cdot \boldsymbol{q} = [\boldsymbol{D}(t) \quad \boldsymbol{A}(t)] \begin{bmatrix} \boldsymbol{q}_D \\ \boldsymbol{q}_A \end{bmatrix}$$

$$= [d_1(t) \ \cdots d_i(t) \cdots \ d_m(t) \ \ a_1(t) \ \cdots a_j(t) \cdots \ a_n(t)] \begin{bmatrix} q_{d1} \\ \vdots \\ q_{di} \\ \vdots \\ q_{dm} \\ q_{a1} \\ \vdots \\ q_{aj} \\ \vdots \\ q_{an} \end{bmatrix} \quad (7)$$

where, B is coefficient matrix of flow state control, $\boldsymbol{q}$ is the array of multi-pumps flow input, $\boldsymbol{D}(t)$ and $\boldsymbol{A}(t)$ are flow state control matrix of digital pumps and analog pumps respectively, $\boldsymbol{q}_D$ and $\boldsymbol{q}_A$ are flow input of digital pumps and analog pumps respectively, $d_i(t)$ ($d_i(t) = 1$ or 0) and q_{di} are the flow state control function and rated flow of the ith digital pump, respectively, $a_j(t)$ ($a_j(t) \in [0 \ 1]$) and q_{aj} are the flow state control function and rated flow of the jth analog pump, respectively.

For example, with binary displacement (1:2:4) digital pumps and one analog pump, the remainder function *mod* is introduced to solve the flow state control matrix.

According to the input command, the percentage of analog pump input control signal is

$$a(t_0) = \frac{1}{q_a} mod[Q(t_0), q_1] \times 100\% \quad (8)$$

In order to get the mathematical expression of digital pumps control signal, it is necessary to introduce the integral function $int(x)$, the control signal can be expressed as

$$d_i(t_0) = int\left\{\frac{1}{q_i}\left[Q(t_0) - \sum_{k=i+1}^{m} d_k(t_0) \cdot q_k\right]\right\} \tag{9}$$

In summary, the output flow of multi-pump source can be expressed as matrix:

$$\boldsymbol{Q}(t_0) = \begin{bmatrix} d_1(t_0) \\ \vdots \\ d_i(t_0) \\ \vdots \\ a(t_0) \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} q_1 \\ \vdots \\ q_i \\ \vdots \\ q_a \end{bmatrix} =$$

$$\begin{bmatrix} int\{[\boldsymbol{Q}(t_0) - d_3(t_0) \cdot q_3 - d_2(t_0) \cdot q_2]/q_1\} \\ \vdots \\ int\{[\boldsymbol{Q}(t_0) - \sum_{k=i+1}^{m} d_k(t_0) \cdot q_k]/q_i\} \\ mod\{\boldsymbol{Q}(t_0),\ q_1\}/q_a \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} q_1 \\ \vdots \\ q_i \\ \vdots \\ q_a \end{bmatrix} \tag{10}$$

Furthermore, the D + A combined multi-pump source output flow range and the state matrix of pumps can be solved under the binary displacement (1:2:4) setting. Assume that the digital pumps output flow is 8 L/min, 16 L/min and 32 L/min in a constant speed, respectively. The analog pump output flow is 28.5L/min. Therefore, the system flow capacities range from 0 to 84.5L/min. The state matrix of pumps corresponding to each kind flow gradation is shown in Table 3.

According to the whole range flow state matrix of D + A combined multi-pump, the pumps control signals are drawn under ramp flow input command, as shown in Fig. 3. Eight periods of time correspond to eight flow ranges. Obviously, the control signal of digital pumps are the square wave with different width, in contrast, that of analog pumps are triangular wave with slope excitation. Once the combination form of D + A identified, the output flow of multi-pump source depends on the flow state matrix completely. Thus, the flow state matrix provides the theoretical basis for designing flow state solver.

Table 3 The flow state matrix with binary displacement ratio of digital pumps

Flow range (L/min)	Flow matrix	Flow range (L/min)	Flow matrix
0 – 8	$Q(t) = [0\ \ 0\ \ 0\ \ a(t)]\begin{bmatrix}8\\16\\32\\28.5\end{bmatrix}$	32 – 40	$Q(t) = [0\ \ 0\ \ 1\ \ a(t)]\begin{bmatrix}8\\16\\32\\28.5\end{bmatrix}$
8 – 16	$Q(t) = [1\ \ 0\ \ 0\ \ a(t)]\begin{bmatrix}8\\16\\32\\28.5\end{bmatrix}$	40 – 48	$Q(t) = [1\ \ 0\ \ 1\ \ a(t)]\begin{bmatrix}8\\16\\32\\28.5\end{bmatrix}$
16 – 24	$Q(t) = [0\ \ 1\ \ 0\ \ a(t)]\begin{bmatrix}8\\16\\32\\28.5\end{bmatrix}$	48 – 56	$Q(t) = [0\ \ 1\ \ 1\ \ a(t)]\begin{bmatrix}8\\16\\32\\28.5\end{bmatrix}$
24 – 32	$Q(t) = [1\ \ 1\ \ 0\ \ a(t)]\begin{bmatrix}8\\16\\32\\28.5\end{bmatrix}$	56 – 84.5	$Q(t) = [1\ \ 1\ \ 1\ \ a(t)]\begin{bmatrix}8\\16\\32\\28.5\end{bmatrix}$

3 Experiment and discussion

3.1 Experiment bed

In order to further verify the feasibility as well as the fundamental control characteristics, a D + A combined multi-pump controlled system experiment bed is built. The system schematic and the experiment bed are shown in Fig. 4 and Fig. 5 respectively. The system mainly includes two parts, one is hydraulic transmission system (main single-rod cylinder and two-rod load simulator), and the other is data acquisition and control system.

The D + A combined multi-pump controlled system mainly consists of digital pumps 5, analog pump 6, relief valves 10, unloading valves 11, proportional valves 18 and other assistant device, etc. The safety pressure is set by relief valves 10, and the system highest pressure is set by proportional relief valves 17. Constant pressure variable displacement pump 4 supplies oil to the load simulator (symmetrical cylinder system) and supplies control oil to other components of the system. With the pump-controlled method of multi-pump source, the proportional valves 18 only play the role of reversing valve. The load simulator can simulate the different working mode, by active and passive loading.

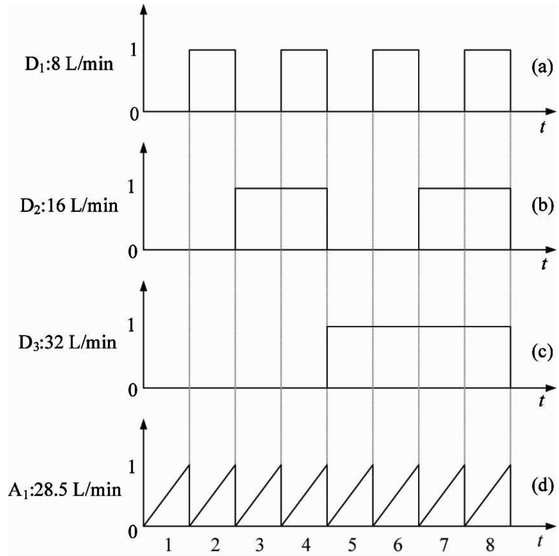


Fig. 3 Control signals of D + A combined multi-pump controlled system under ramp flow command

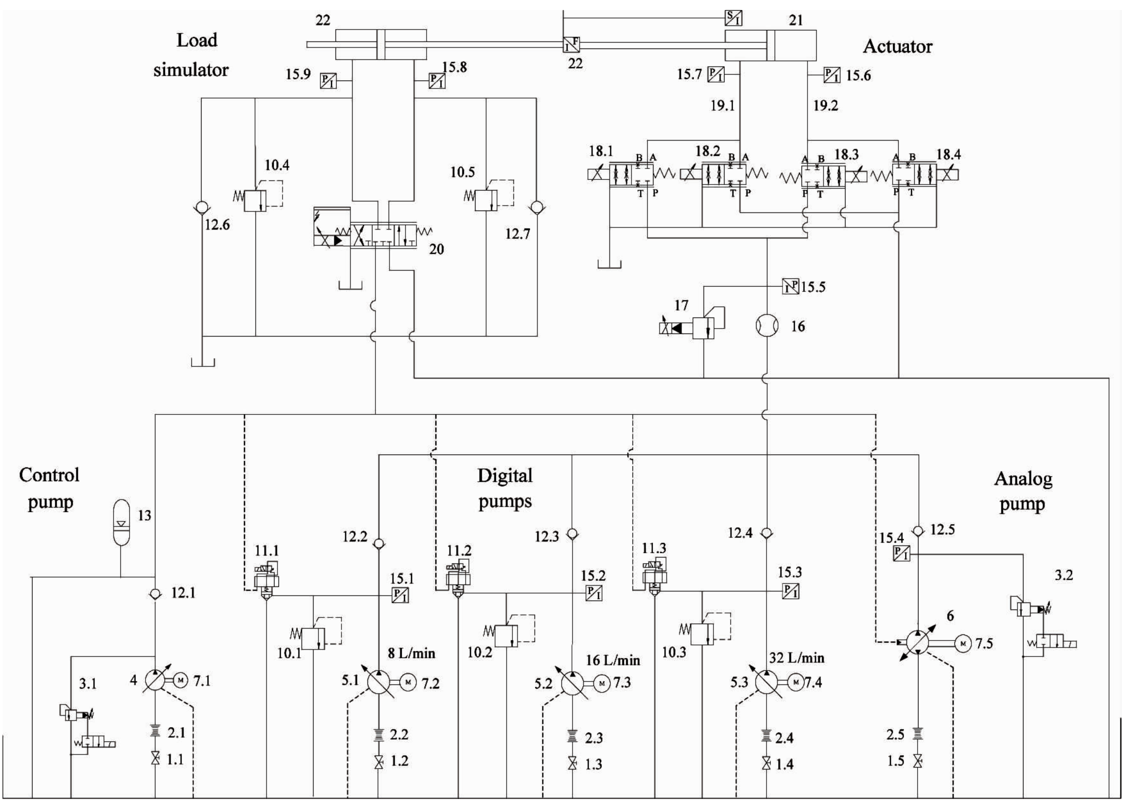
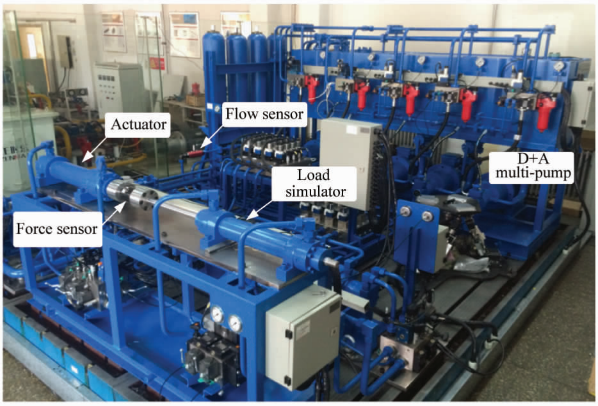
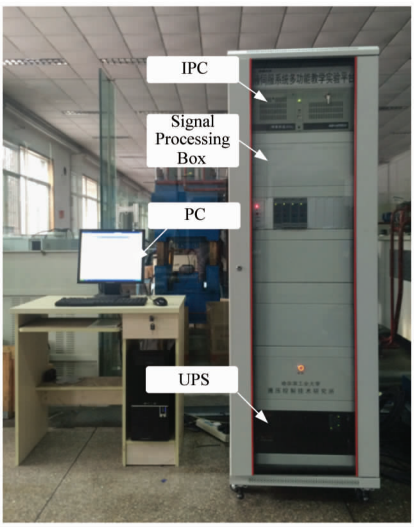


Fig. 4 Experimental schematic of D + A combined multi-pump controlled system

The signal control and acquisition system for D + A combined multi-pump controlled system is shown in Fig. 5(b). According to the flow state matrix, a flow state solver is designed on MATLAB/Simulink software in personal computer (PC), and the control signals are sent to industrial personal computer (IPC) to control actuator directly in real time. Digital signals from IPC are sent to the on/off valve matrix to select the corresponding flow gradation of digital pumps. At the same time, the IPC is responsible for signal acquisition, thus flow data, pressure and displacement data could be collected and then processed by the real time controller with 0.1s sample interval. Moreover, the user interface could help to monitor the data and control process, as well as adjust some system parameters. The related parameters of experiment rig are list in Table 4.



(a) D + A combined multi-pump controlled system



(b) Data acquisition and control system

Fig. 5 Experiment bed

Table 4 Parameters of experiment rig

Name	Stroke	Signal	Note
Digital pumps	8/16/32 L/min	0 or 24V	
Analog pump	0 – 28.5 L/min	0 – 10V	80ms
Position sensor	400mm	4 – 20mA	0.1% FS
Flow sensor	60 L/min	4 – 20mA	2%
Pressure sensor	250 bar	4 – 20mA	0.5% FS
Force sensor	20 kN	4 – 20mA	0.05% FS

3.2 Flow characteristics analysis of multi-pump source

In this part, this study investigates the flow characteristics of each pump in multi-pump source, which lays experimental foundation for D + A combined control follow-up. In these experiments, the system safety pressure is set as 100 bar.

1) Flow step characteristics of digital pump

The flow step characteristics of three digital pumps with binary displacement, 8L/min, 16L/min and 32L/min, are shown in Fig. 6. It can be seen that the greater the displacement of digital pumps is, the shorter the time is to reach steady flow in given experiment rig.

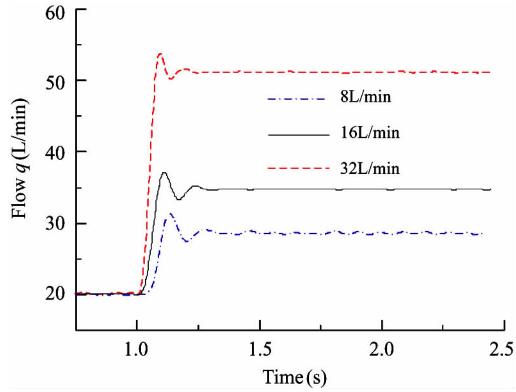
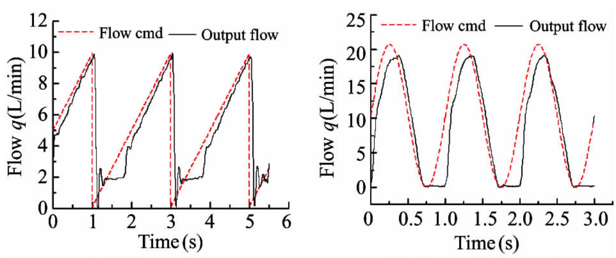


Fig. 6 Flow step characteristics of digital pumps

2) Flow characteristics of analog pump

The experimental results for triangular wave and sinusoid input signal are shown as Fig. 7. The flow output tracks the input signal well, except the small flow state. When the displacement of analog pump drops to zero suddenly, there is a flow dead-zone in output for the triangular wave and sinusoid input signal. The main reason is that the smaller the flow output of the analog pump is, the more the pressure setup time is. Besides, the check valve behind the analog pump needs response time to make the system pressure reach the open force of the spring of the check valve.



(a) Triangular wave (b) Sinusoid input signal

Fig. 7 Flow characteristics of analog pump

3) Flow characteristics of D + A combined multi-pump

Based on what discussed above, in order to get the flow characteristics of D + A combined multi-pump source, the load pressure is set 80 bar for the ramp input 50L/min and 50 bar for sinusoid input at 25L/min amplitude by proportional relief valve passively, respectively. The experimental results are shown in Fig. 8.

The flow follows the ramp signal basically, but it still had delay and deviation , particularly to the small

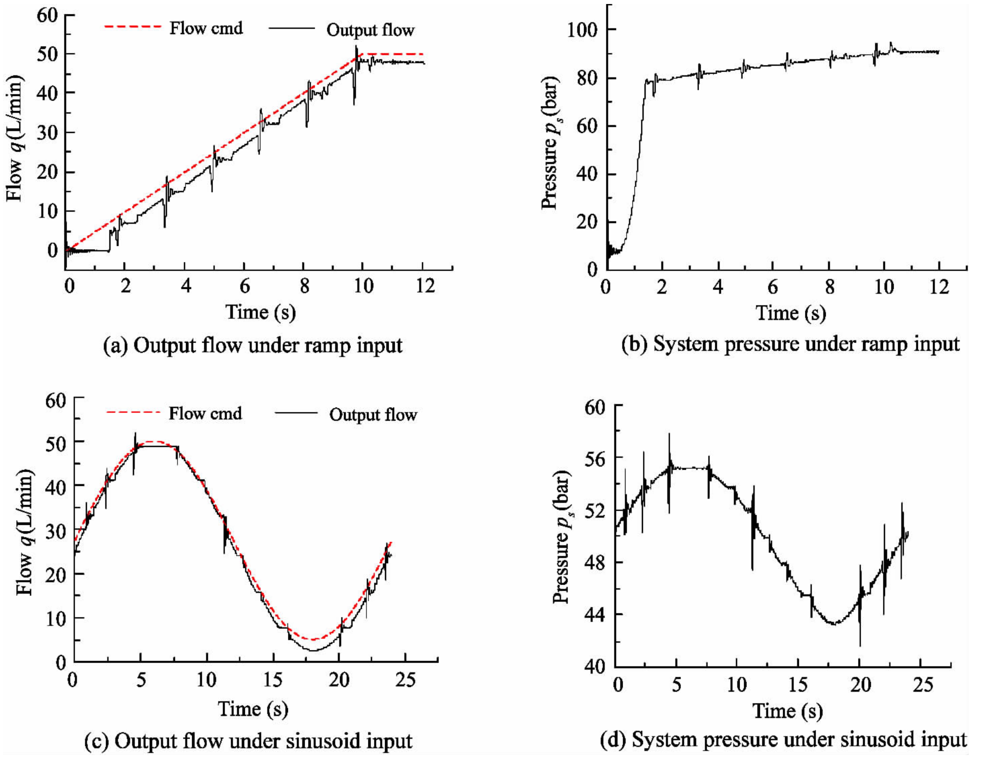


Fig. 8 Fundamental characteristics of D + A combined multi-pump source

flow output (close to 0L/min) of the analog pump. When digital pumps switched, the corresponding flow impact would occurr as well as system pressure oscillations. Comparing to ramp signal, the sinusoid had smaller follow deviation. However, a horizontal segment appeared at the peak, not in the valley. The reason is that at 5s, the flow requirement was about 48.6L/min, the analog pump just supplied a small outflow about 0.6L/min. Therefore, it would take a long time to reach system pressure. Vice versa, it needed relative greater outflow 6L/min at 18s, thus, it would need a short time to meet the flow requirements.

3.3 Flow characteristics analysis of D + A combined multi-pump controlled cylinder system

The load simulator set loads pressure as 35 bar by the relief valves. Given the ramp flow input signal, the experimental results of flow rate and pressure as well as the control signal of each pump based on the theoretical solution are shown in Fig. 9 and Fig. 10 respectively.

Due to the system volume effect and the open-loop control, the lag and deviation of the system output flow as well as velocity and position of the cylinder occurred in the following process. When on/off valves switched, the flow impact and pressure oscillations occurred. However, there is no jitter reflected in cylinder position. It is obvious that the system pressure is no more than 100 bar until the cylinder piston reached the maximum stroke 400mm at 10s, without overflow losses in the following process. Therefore, D + A combined multi-pump controlled cylinder open-loop control system is feasible, but without high precision.

It can be seen that the maximum displacement digital pump is used few times, while the small-displacement digital pumps are used more times. The analog pump control signal is changing all the time with the load requirements. This phenomenon is consistent with the previous theory of flow state matrix.

4 Conclusion

This paper proposes a novel concept of D + A combined multi-pump controlled system, and adopts the pump-controlled method to investigate its feasibility and fundamental characteristics. First, the working principle, flow region division method and evaluation indicators are introduced. The flow state matrix of binary-coding digital pumps is determined uniquely by theoretical solution, and then the flow state solver is designed on MATLAB/Simulink software. Furthermore, the flow fundamental characteristics are obtained and analyzed via experiment. The experimental results show that though there is a little lag behind flow input signal, the D + A combined multi-pump controlled system tracks flow input signal well with acceptable flow deviation. Therefore, this system is verified feasible and could achieve good control effect in pump-controlled mode, without overflow losses, which could provide theoretical guidance for saving-energy of large flow and heavy machinery.

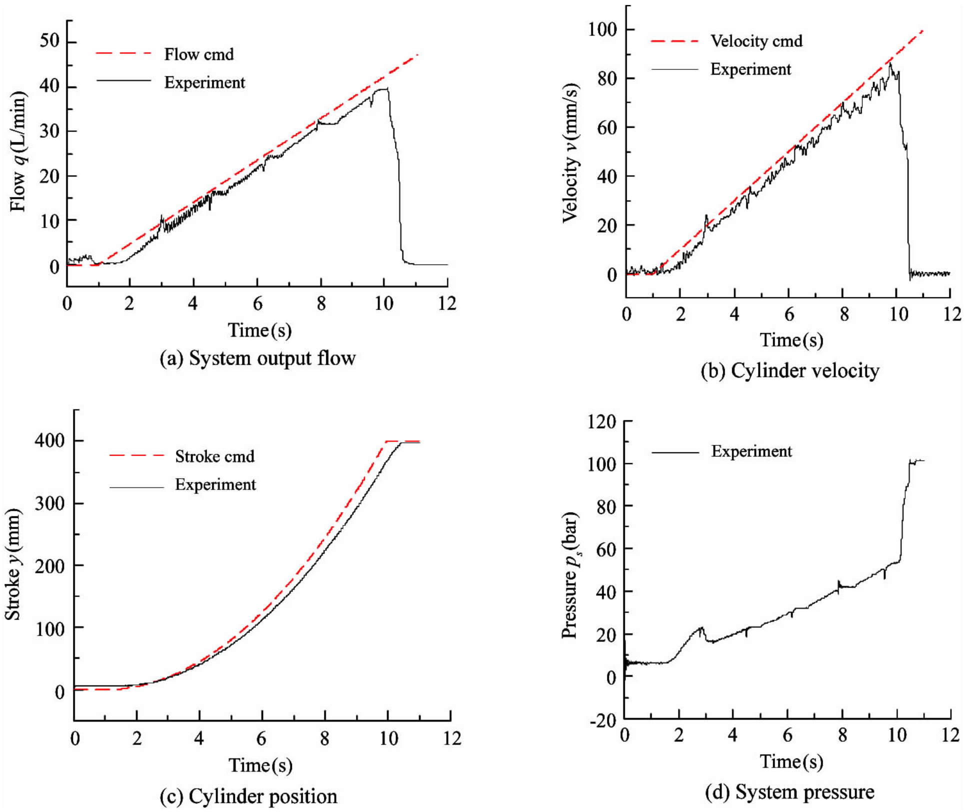


Fig. 9 Fundamental characteristics under ramp flow input

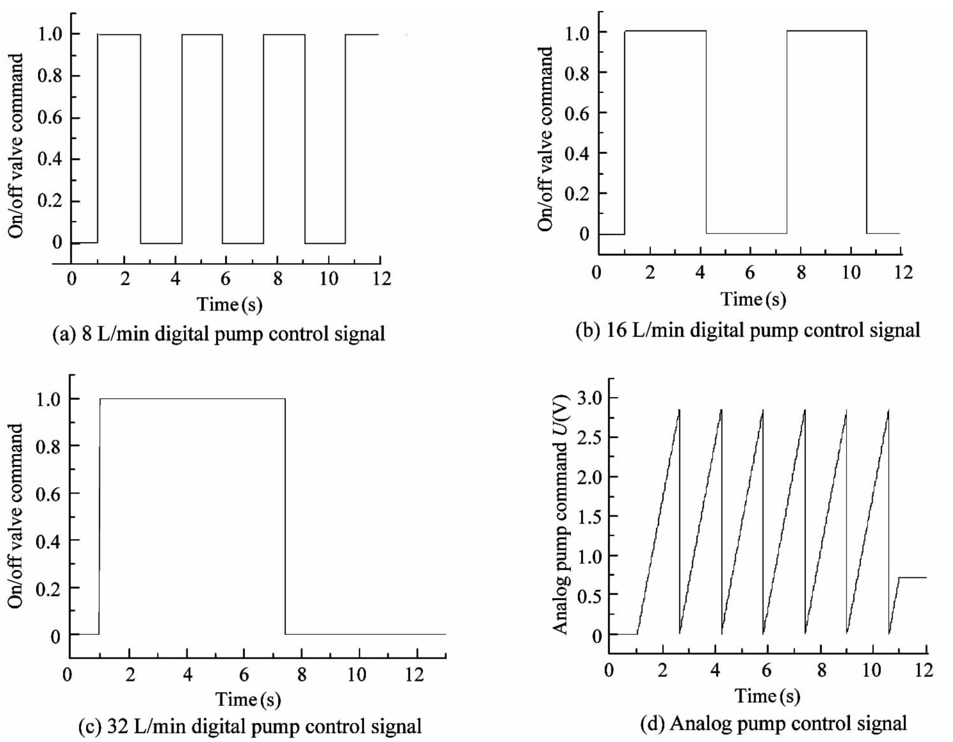


Fig. 10 Control signal of D + A multi-pump under ramp input

The proposed method and configuration is in early stage, challenges worthing further study are flow impact and pressure oscillations caused by on/off valve switching. Also, in order to get better control accuracy, particularly at low speeds, this paper opens the door for future research in areas such as pump-valve combined control strategy, and pressure and flow compensation.

References

[1] Williamson C, Ivantysynova M. Power optimization for multi-actuator pump-controlled systems [C]. In: Proceedings of the 7th Workshop International Fluid Power Conference, Aachen, Germany, 2010. 91-102

[2] Zimmerman J, Ivantysynova M. Hybrid displacement controlled multi-actuator hydraulic system[C]. In: Proceedings of the 12th Scandinavian International Conference on Fluid Power, Tampere, Finland. 2011. 952-978

[3] Busquets E, Ivantysynova M. A multi-actuator displacement-controlled system with pump switching: a study of the architecture and actuator-level control[J]. *JFPS International Journal of Fluid Power System*, 2015, 8: 66-75

[4] Busquets E, Ivantysynova M. Toward supervisory-level control for the energy consumption and performance optimization of displacement-controlled hydraulic hybrid machines[C]. In: Proceedings of the 10th IFK International Conference on Fluid Power, Dresden, Germany, 2016. 163-174

[5] Linjama M. Digital fluid power-state of the art[C]. In: Proceedings of the 12th Scandinavian International Conference on Fluid Power, Tampere, Finland, 2011. 18-20

[6] Linjama M, Huova M, Boström P, et al. Design and implementation of energy saving digital hydraulic control system[C]. In: Proceedings of the 10th Scandinavian International Conference on Fluid Power, Tampere, Finland, 2007. 1-19

[7] Linjama M, Huhtala H. Digital hydraulic power management system: towards lossless hydraulics[C]. In: Proceedings of the 3rd Workshop on Digital Fluid Power, Tampere, Finland, 2010. 13-14

[8] Linjama M, Laamanen A, Vilenius M. Is it time for digital hydraulics[C]. In: Proceedings of the 8th Scandinavian International Conference on Fluid Power, Tampere, Finland, 2003. 347-366

[9] Linjama M, Huova M, Huhtala K. Model-based force and position tracking control of an asymmetric cylinder with a digital hydraulic valve[J]. *International Journal of Fluid Power*, 2016: 163-172

[10] Paloniitty M, Linjama M, Huhtala K. Equal coded digital hydraulic valve system: improving tracking control with pulse frequency modulation[J]. *Procedia Engineering*, 2015, 106: 83-91

[11] Rampen W H S, Salter S H. Modeling of digital-displacement pump-motors and their application as hydraulic drives for nonuniform loads[J]. *Journal of Dynamic Systems Measurement & Control*, 2000, 122(1): 210-215

[12] Payne G S, Kiprakis A E, Ehsan M, et al. Efficiency and dynamic performance of digital displacement(TM) hydraulic transmission in tidal current energy converters [J]. *Proceedings of the Institution of Mechanical Engineers Part A Journal of Power & Energy*, 2007, 221(2): 207-218

[13] Merril K J, Lumkes J H J. Operating strategies and valve requirements for digital pump/motors[C]. In: Proceedings of the 6th FPNI-PhD Symposium, West Lafayette, USA, 2010. 249-258

[14] Heitzig S, Theissen H. Aspects of digital pumps in closed circuit[C]. In: Proceedings of the 4th Workshop on Digital Fluid Power, Linz, Austria, 2011. 39-50

[15] Heitzig S, Sgro S. Energy efficiency of hydraulic systems with shared digital pumps[J]. *International Journal of Fluid Power*, 2012, 13(3): 49-57

[16] Laamanen A, Linjama M, Vilenius M. On the pressure peak minimization in digital hydraulics[C]. In: Proceedings of the 10th Scandinavian International Conference on Fluid Power, Tampere, Finland, 2007. 107-121

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