JST: Smart Systems and Devices
Volume 35, Issue 1, January 2025, 057-064

A Study on Speed Tracking Control for Hydraulic Linear Actuators Using High Speed on/off Valves

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Abstract

The paper presents a study on speed control of hydraulic linear actuators without servo valves. A typical hydraulic circuit, including a cylinder, a set of four throttle valves, and four high-frequency directional control valves, is implemented. The characteristics of components are mathematically modeled and numerically investigated in MATLAB/Simulink. The research exploited a combination of rule-based control algorithm and pulse-width modulation for oil flow rate control, thereby controlling the piston speed. The control process is carried out in two stages. In the first stage, the rule-based control algorithm makes piston speed track the set value with rough error. Pulse-width modulation is then applied to a certain high-frequency valve to help the speed closely match the desired value in the second stage. The obtained simulation results show that speed tracking control is guaranteed. Thus, the advantages of pulse-width modulation control are not only promoted, but the pulse regulation frequency for high-speed on/off valve is also significantly reduced. The control method can be considered as an effective solution for controlling accurately the speed of the hydraulic systems instead of using servo valves.

Keywords: Hydraulic control, PWM, rule-based control.

1. Introduction

Precision hydraulic control systems are used as an essential part of industrial systems. Along with the development of science and technology, more and more solutions for this problem are being researched and widely applied. The option of using linear valves (proportional and servo valves) and conventional control with improvement is the most popular. This research direction has been attracting the attention of many researchers, notably: Piotr Woś and Ryszard Dindor [1 - 3], Juncheng Mi *et. al*. [4]. However, this option requires high costs in terms of materials such as valves and oil purity. The need to replace linear valves is of concern to many other researchers. Nowadays, the high-speed on/off valve (HSV) seems to be a solution of replacing linear valve in hydraulic and pneumatic systems because of its advantages such as: fast switching, compactness and low cost (shown in Fig. 1). This type of valve is often combined with a pulse signal controller. Some typical research in this direction can be mentioned as: Qi Zhong *et. al*. applied an intelligent pulse-width modulation control for HSV performance analysis [5], Qiang Gao *et. al*. [6] took a review on research status and prospects of control strategies for HSV on/off valves. In these studies, many control strategies are compared and some suggestions are offered. However, innovation in technology is unlimited. This research field keeps attracting the attention of many researchers for any research gaps. For example, most studies only focus on pulse signals, their rules and pulse widths, but ignore the characteristics of the hydraulic equipment part.

In this paper, a typical of hydraulic linear actuator is executed for speed tracking. The actuator is controlled by four on/off valves, which are combined with four throttle valves having different opening areas on the oil line. A rule-based control algorithm and pulse-width modulation (PWM) are used to control piston speed. The control algorithm will provide coarse control command and PWM can adjust the fine control signal for the system to operate. The detailed content will be presented hereunder.

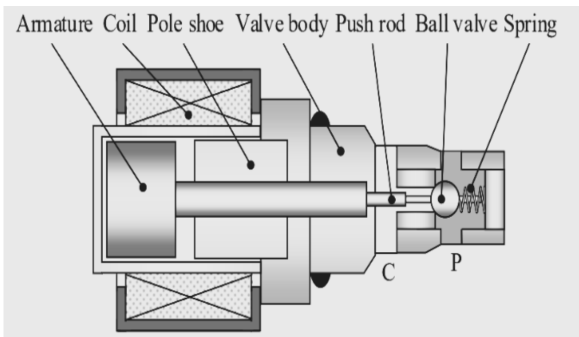

Fig. 1. Structure diagram of the HSV driven by a solenoid

ISSN 2734-9373
https://doi.org/10.51316/jst.179.ssad.2025.35.1.7
Received: Jun 24, 2024; revised: Oct 25, 2024;
accepted: Dec 9, 2024

2. Hydraulic Circuit

The Fig. 2 shows a schematic diagram of hydraulic linear actuator. The main components are: (1) one-side rod hydraulic cylinder, (2) 4/3 directional control valve, (3) four high-speed 2/2 directional control valves, (4) four throttle valves and a hydraulic source unit (including oil tank, oil supplying pump, relief valve, filter). The four throttle valves are set to open at: 5%, 15%, 30%, and 50% respectively. The 4/3 valve decides whether the cylinder protrudes or retracts according to applying control signal on its magnetic coins. Each 2/2 valve along with its corresponding throttle valve will operate to control cylinder speed by controlling flow rate into cylinder.

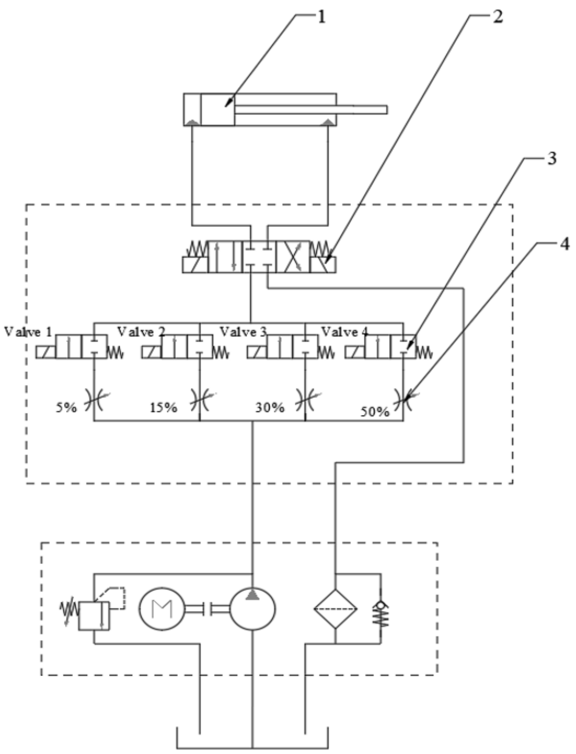

Fig. 2. The schematic diagram of hydraulic circuit

By this way, piston rod can operate at many different speeds depending on which 2/2 valve is implemented.

3. The Rule-Based Control Algorithm and System Modeling

In this section, the research develops a rule-based control algorithm and the analysis model of hydraulic cylinder actuator. Then the whole model is implemented in MATLAB/Simulink for convenient investigation.

As mentioned above, the speed of hydraulic cylinder is controlled by four high speed on-off valves (HSV): valve 1, valve 2, valve 3, valve 4. When using only one HSV to track speed as the research of Qi Zhong [5], the HSV on-off frequency is high. So, the service life of the valve is seriously affected. Therefore, four HSVs are used alternately to help improve this problem. The speed is determinded by the flow rate supplied into cylinder chamber. The 4/3 directional valve just only controls the flow into piston chamber or rod chamber depending on protrudes or retracts process. The four HSVs have the same maximum flow rate (Q_{vm} = 0.25 l/s) but the corresponding throttle valves have different openings. Using four throttles valve with diffirent opening areas to divide the maximum flow rate through each HSV helps accommodate a more variable flow rate range. Thus the accuracy of the system is increased. The desired input speed has a linear value corresponding to the linear flow rate value. At each time, the valve's state is open or closed depending on the required speed. Table 1 shows the open and closed states of HSVs. For each desired flow value range, the state of each HSV is expected to be open and closed. Positions marked with X in Table 1 represent open valves, otherwise closed valves. In case $Q < Q_1$ and the error between the desired value and the actual value is higher than 0.5%, pulse width modulation (PWM) is used to make error lower than 0.5%. In case $Q > Q_m$, all HSVs are fully opened, and the error is approximately 0%. In which, Q is the desired flow rate of system; Q_1, Q_2, Q_3, Q_4 is the maximum flow rate through each HSV; $Q_{xyz} = Q_x + Q_y + Q_z$.

Table 1. Rule-based control algorithm

Q	Q_1	Q_2	Q_3	Q_4
$Q<Q_1$				
$Q_1 \le Q<Q_2$	X			
$Q_2 \le Q<Q_{12}$		X		
$Q_{12} \le Q<Q_3$	X	X		
$Q_3 \le Q<Q_{13}$			X	
$Q_{13} \le Q<Q_{23}$	X		X	
$Q_{23} \le Q<Q_4$		X	X	
$Q_4 \le Q<Q_{14}$				X
$Q_{14} \le Q<Q_{24}$	X			X
$Q_{24} \le Q<Q_{124}$		X		X
$Q_{124} \le Q<Q_{34}$	X	X		X
$Q_{34} \le Q<Q_{134}$			X	X
$Q_{134} \le Q<Q_{234}$	X		X	X
$Q_{234} \le Q<Q_m$		X	X	X
$Q=Q_m$	X	X	X	X

Thus, with the requirement of variable speed, the valves will be opened and closed continuously. However, the operating frequency of the valve is limited. Moreover, there are some ranges of flow rate that rule-based control method cannot accommodate. Therefore, pulse-width modulation controller is used to solve this problem. For each range of desired flow rate values, HSVs are rotated to use PWM method. This order is shown in Table 2.

Table 2. Rules of PWM usage for HSVs

Q required	Valve
Q<Q1	1
Q1≤Q<Q2	2
Q2≤Q<Q12	1
Q12≤Q<Q3	3
Q3≤Q<Q13	1
Q13≤Q<Q23	2
Q23≤Q<Q4	1
Q4≤Q<Q14	1
Q14≤Q<Q24	2
Q24≤Q<Q124	1
Q124≤Q<Q34	3
Q34≤Q<Q134	1
Q134≤Q<Q234	2
Q234≤Q<Qm	1

In pulse control signals, the digital command signal (DCS) is an alternating signal that switches between "logical one" and "logical zero" states, which are represented by the pulse duration (t_{on}) and the pause time (t_{off}), respectively [7]. The sum of the pulse duration (t_{on}) and the pause time (t_{off}) gives the overall period (T) of the DCS:

$$T = t_{on} + t_{off} \tag{1}$$

The behavior of an HSV (poppet-type design) changes depending on how the control variable of the DCS is modulated. There are five distinct operation modes.

+ Deactivated Mode: the pulse duration (t_{on}) is so short that the poppet does not move.

+ Ballistic Mode: increasing the pulse duration (t_{on}) the poppet starts to move, but it does not reach the upper end stop and is pushed back to the lower end stop.

+ Normal Mode: the pulse duration (t_{on}) is long enough to fully open the valve.

+ Inverse Ballistic Mode: the pause time (t_{off}) is so short that the poppet cannot reach the lower end stop.

+ Activated Mode: the pause time (t_{off}) is so short that the valve remains always open.

The pulse width modulation is method controlling the pulse duration (t_{on}) while keeping the period (T) or the switching frequency ($f=1/T$) constant. This leads to modify the duty cycle (τ) of the DCS.

$$\tau = \frac{t_{on}}{T} \tag{2}$$

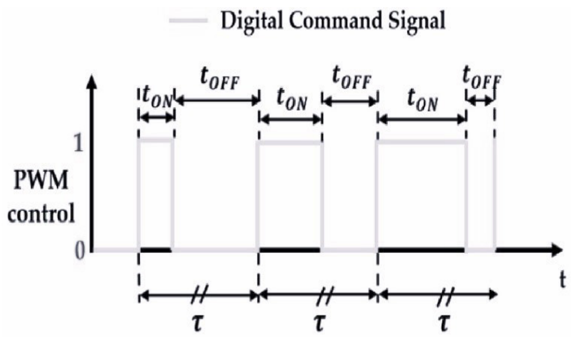

Fig. 3. PWM method

The relationship between the openness of HSV (Q_v) and PWM signal (τ) is determined by the on-off characteristics of high speed on-off valve and its mathematical model. The functional relationship between the openness of HSV and the duty of PWM signal is shown as equation (3).

$$Q_v = \begin{cases} 0 & \tau \in [0, \tau_1) \\ \frac{1}{2}\left(\frac{\tau_2+\tau_4}{\tau_2^{\,2}}\right)(\tau+\tau_{yc1}-\tau_1)^2 Q_{vm} & \tau \in [\tau_1, \tau_{12}) \\ \left[\left(\frac{\tau_2+\tau_3}{\tau_2}\right)\tau - \tau_1 - \frac{\tau_2}{2} + \frac{\tau_4}{2} - \frac{\tau_1\tau_3}{\tau_2}\right] Q_{vm} & \tau \in [\tau_{12}, \tau_{on}) \\ \left(\tau+\tau_3-\tau_1+\frac{\tau_4-\tau_2}{2}\right) Q_{vm} & \tau \in [\tau_{on}, 1-\tau_{off}) \\ \left(\tau+\tau_3-\tau_{yc2}+\frac{\tau_4-\tau_2}{2}\right) Q_{vm} & \tau \in [1-\tau_{off}, \tau_{34}) \\ \left[1-\frac{(\tau+\tau_3-\tau_{yc2}-1)^2}{2\tau_4}-\frac{\tau_2(\tau+\tau_3-\tau_{yc2}-1)^2}{2\tau_4^{\,2}}\right] Q_{vm} & \tau \in [\tau_{34}, 1-\tau_3) \\ Q_{vm} & \tau \in [1-\tau_3, 1] \end{cases} \tag{3}$$

where T is overall period of the DCS; t_1 is the delay-closed time; t_2 is the move-closed time; t_3 is the delay-released time; t_4 is the move-released time.

$\tau_1 = t_1/T$; $\tau_2 = t_2/T$; $\tau_3 = t_3/T$; $\tau_4 = t_4/T$; $\tau_{yc1} = (\tau - \tau_1)\tau_3 / \tau_2$

$\tau_{yc2} = (1 - \tau - \tau_3)\tau_1 / \tau_4$ $\tau_{12} = \tau_1 + \tau_2^{\,2} / (\tau_2 + \tau_3)$;

$\tau_{on} = \tau_1 + \tau_2$; $\tau_{34} = 1 - \tau_3 + \tau_4^{\,2} / (\tau_1 + \tau_4)$; $\tau_{off} = \tau_3 + \tau_4$

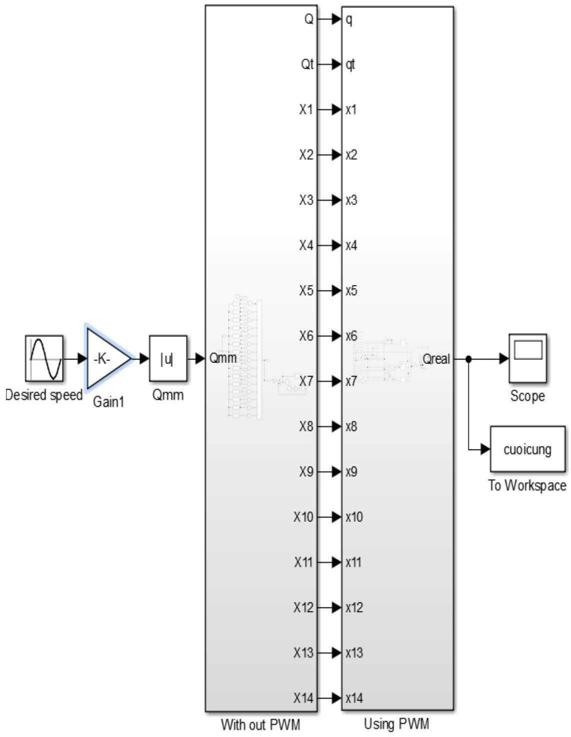

Fig. 4. The whole model in Simulink

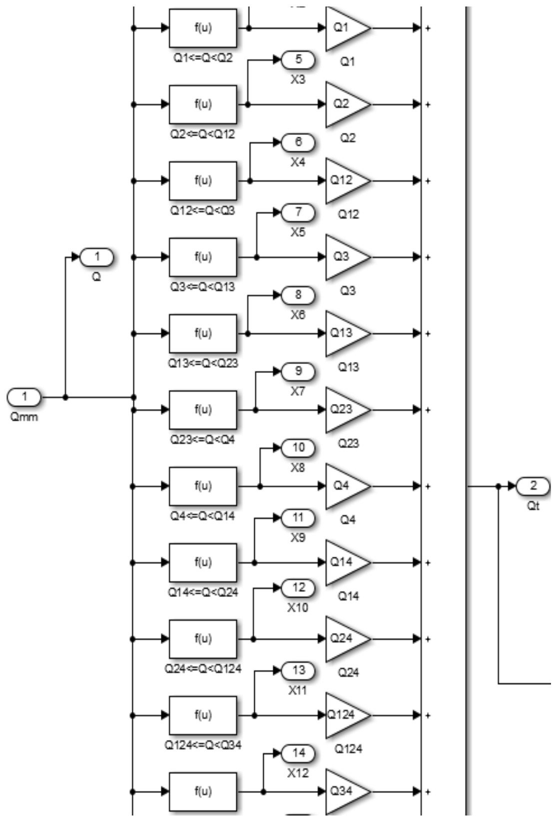

Fig. 5. The rule-based control algorithm

The flow rate through the valve when using the PWM method is shown as follows:

$$Q_x = \begin{cases} Q_i f \tau & \text{if } Q_i < Q_v \\ Q_v f \tau & \text{if } Q_i > Q_v \end{cases} \tag{4}$$

where Q_i ($i=1;2;3;4$) is the maximum flow rate through each HSV; Q_v is the flow rate through HSV when using PWM method.

The speed error (e) between the desired speed and simulated speed is shown as equation (5).

$$e = |v_r - v_s| \tag{5}$$

where v_r is the desired speed; v_s is the simulated speed.

Base on the control algorithm and valve characteristics that have been built, the entire model is set up on MATLAB/Simulink as shown in Fig. 4. The rule-based control algorithm is in Fig. 5. The PWM control models of 3 valves: valve 1, valve 2, valve 3 are in subsystem expressed in Fig. 6, Fig. 7 and Fig. 8, respectively.

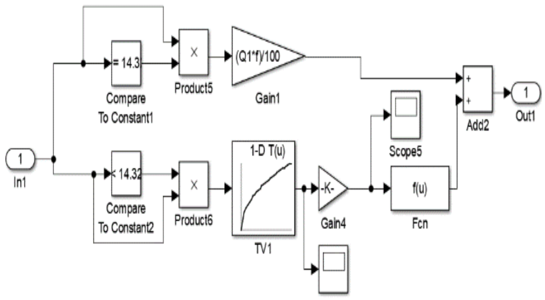

Fig. 6. The PWM control model in Simulink of valve 1

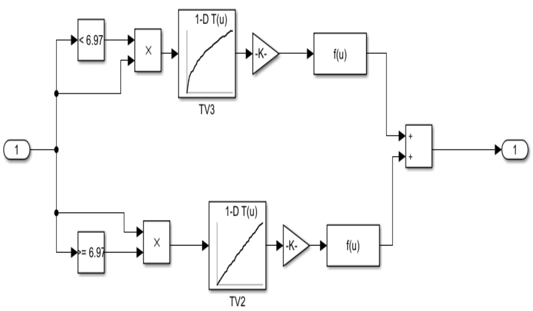

Fig. 7. The PWM control model in Simulink of valve 2

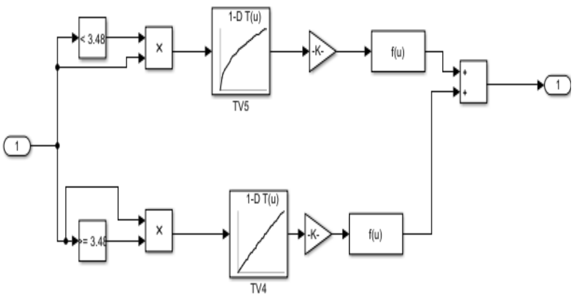

Fig. 8. PWM control model in Simulink of valve 3

With the developed control algorithm and calculation program built in Simulink, the system's operation will be investigated by numerical simulation.

4. The System Simulation and Results

In the previous section, a calculation model and rule-based control of system are developed and built up in MATLAB/Simulink. This section shows numerical simulation results and response of system corresponding to desired conditions. The 2/2 high-speed valves used have a maximum frequency of 4Hz [8]. The two sets of system parameters are shown in following tables. The study implements simulation in two cases: when using only rule-based control and using rule-based control combined with PWM.

Table 3. The first set of system parameters

Quantity/Factor	Value (unit)
Cylinder parameter (Bore/rod)	0.1/0.07 (m)
Maximum speed	0.03 (m/s)
t_1	30.10^{-3} (s)
t_2	$16,4.10^{-3}$ (s)
t_3	27.10^{-3} (s)
t_4	17.10^{-3} (s)
T	0.25 (s)

With the first set of parameters in Table 3, the results obtained of the former case are shown from Fig. 9 to Fig. 14. Flow and speed characteristics coincide in both cases, that reflects the physical nature of the system. In these cases, desired speed is the speed that system want to reach, and it has sin wave shape: v_r=0.03*sin($2\pi*t$) (m/s). Corresponding to that is the desired flow rate put into piston chamber: $Q_r=v_r*A$=0.2356* sin($2\pi*t$) (l/s).

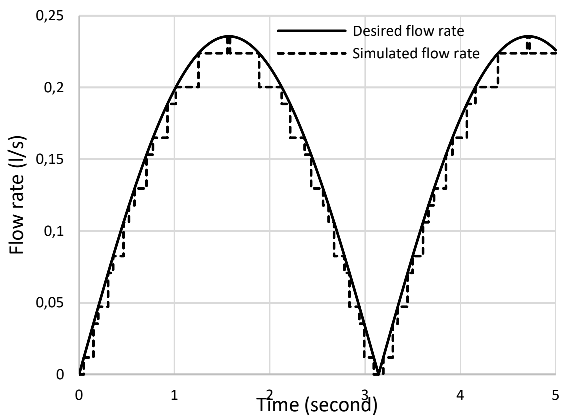

Fig. 9. Flow rate of the system when using only rule-based control

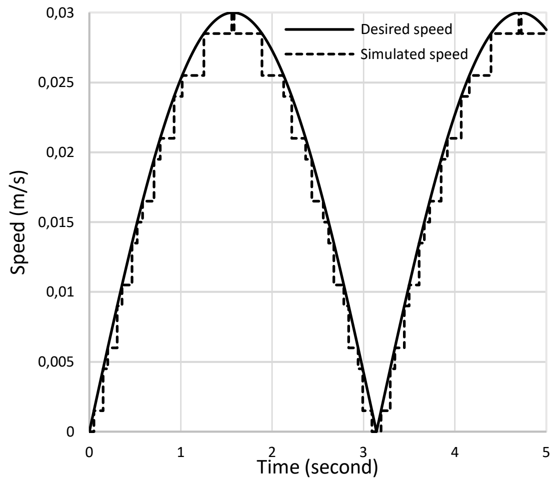

Fig. 10. Speed performance of the system when using only rule-based control

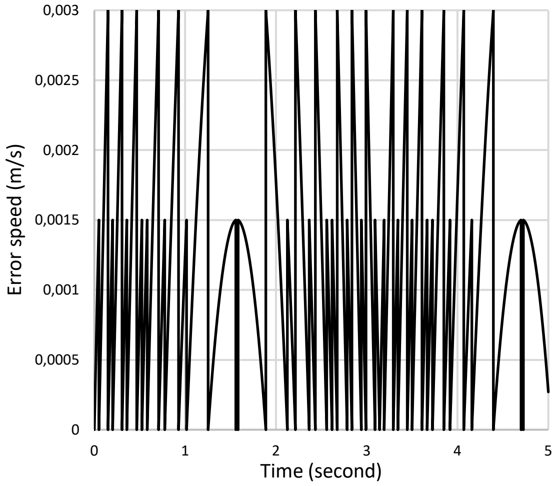

Fig. 11. Speed error of the system when using only rule-based control

When using only rule-based control, the error is relatively large. So, in order to reduce the error, PWM method is combined with rule-based control.

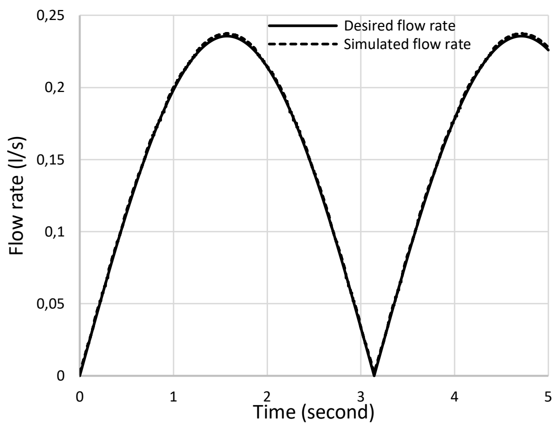

Fig. 12. Flow rate of the system when using rule-based control combined with PWM

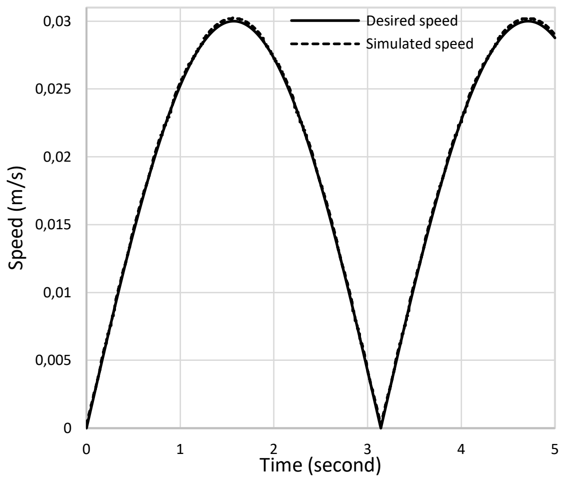

Fig. 13. Speed performance of the system when using rule-based control combined with PWM

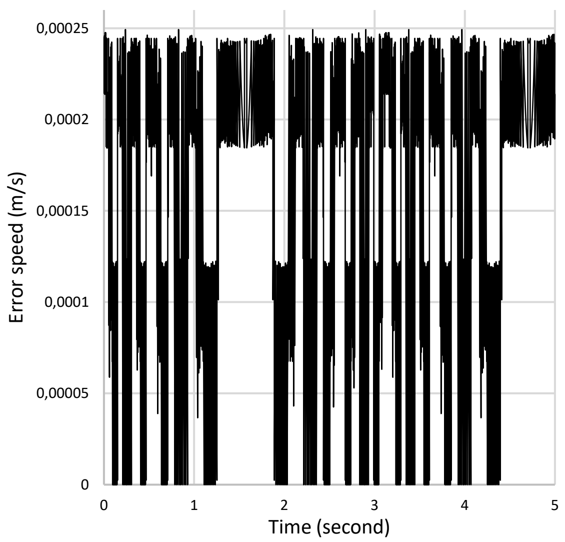

Fig. 14. Speed error of the system when using rule-based control combined with PWM

The differences of accuracy between two cases are very clear. When using only rule-based control, the cylinder's speed tracks the desired value with a quite large error (3×10^{-3} m/s). The error is reduced much smaller when using rule-based control combined with PWM (2.5×10^{-4} m/s). It can be said that the rule-based controller makes the speed track quite well to desired values, then PWM makes the speed almost match desire.

For demonstrating the response ability of the control algorithm, the simulation is implemented with another hydraulic cylinder configuration as in Table 4. The obtained results are in Fig. 15 to Fig. 20. They are completely like the former results. In which, desired speed has sin wave shape: v_r=0.019*sin(2π*t) (m/s).

Table 4. The second set of system parameters

Quantity/Factor	Value (unit)
Cylinder parameter (Bore/rod)	0.125/0.07 (m)
Maximum speed	0.019 (m/s)
t_1	30.10^{-3} (s)
t_2	$16,4.10^{-3}$ (s)
t_3	27.10^{-3} (s)
t_4	17.10^{-3} (s)
T	0.25 (s)

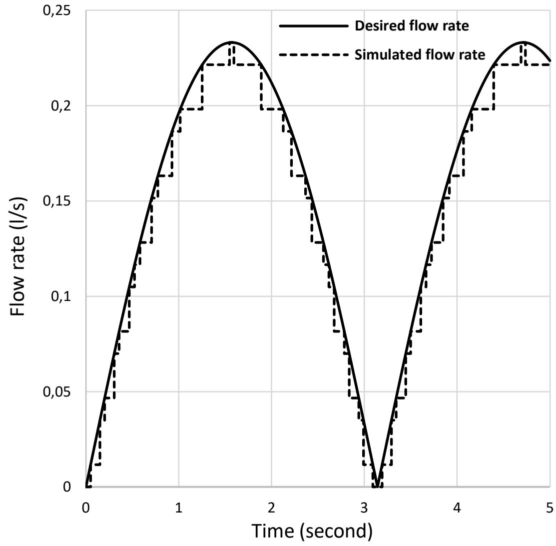

Fig. 15. Flow rate of the system when using only rule-based control

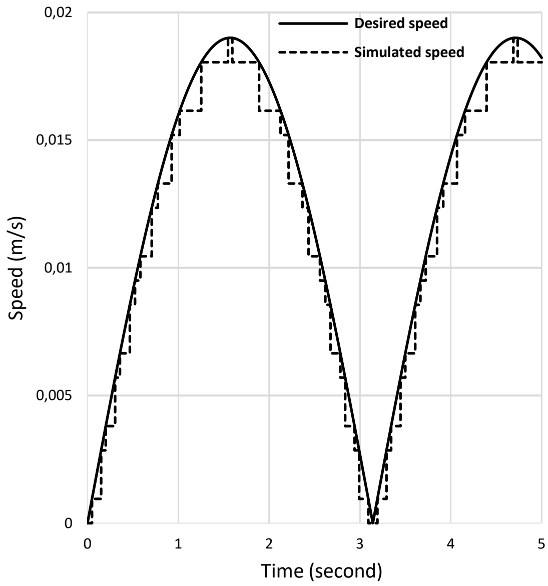

Fig. 16. Speed performance of the system when using only rule-based control

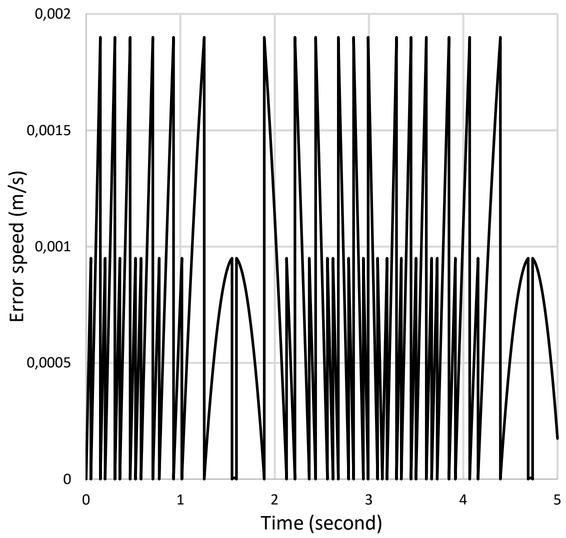

Fig. 17. Speed error of the system when using only rule-based control

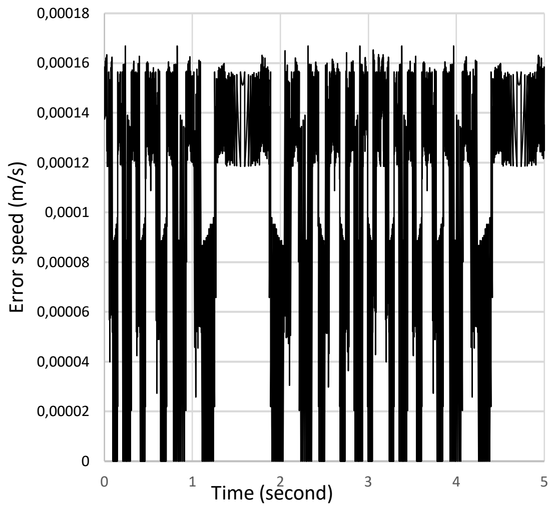

Fig. 20. Speed error of the system when using rule-based control combined with PWM

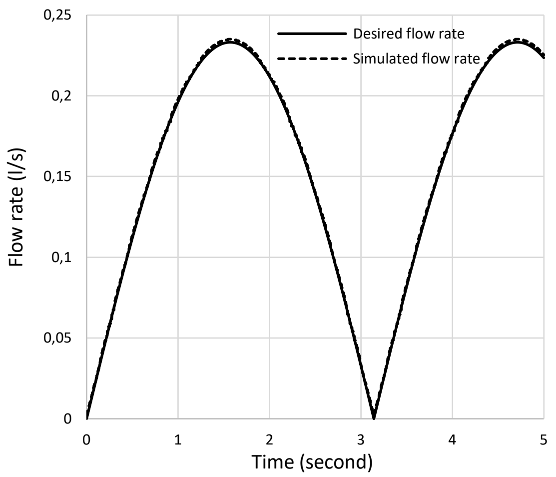

Fig. 18. Flow rate of the system when using rule-based control combined with PWM

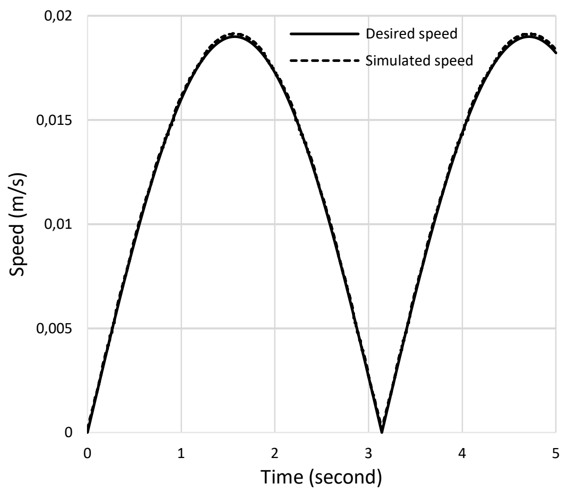

Fig. 19. Speed performance of the system when using rule-based control combined with PWM

The close similarity between the flow rate and speed curves in these figures reflects the essential nature of hydraulic transmission, where oil compressibility is inconsiderable. This compressibility is a factor that has a significant influence on the accuracy of position control in hydraulic systems. However, for speed control problems, the valves operate at high speed with PWM, so the speed error is adjusted continuously. That leads to greatly reduced speed errors. Therefore, the obtained simulation results are reliable when they accurately reflect the physical nature of the system and ensure the logic of the problem.

With the two different cylinder parameters, the rule-based control has a very significant value as it can make the system track desired quite well. Based on this achievement, the PWM operates very effectively, both ensuring accuracy requirements and helping to reduce the working frequency of each HSV. In other words, it leads to increasing the service time of HSVs.

5. Conclusion

This study offers a solution of speed control of hydraulic actuator based on on-off valves. A combination of rule-based control and pulse-width modulation is established for both ensuring speed accuracy and increasing the service time of HSVs. This is useful in the field of hydraulic control without servo equipment. The obtained results are the basis for further research in related fields such as control optimization, intelligent control, etc.

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