Study on Flow Characteristics and Linearization of
Pneumatic High-Speed On-off Valve

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Abstract. It is hard to model the dynamic flow rate of pneumatic high-speed on-off valve due to its dead zone and nonlinearity. The average opening ratio was proposed to describe the dynamic flow rate after systematically analyzing the spool action characteristics. The mathematical relationship between flow rate, frequency, and duty cycle was established. Experimental results show that the method can accurately reflect the dynamic flow characteristics. Finally, a piecewise linearization method is designed to make the flow rate proportional to the input.

1. Introduction

Pneumatic high-speed on-off valves (PHSV) have been widely used in the industrial field due to their advantages of low cost, strong anti-pollution ability, and quick switching [1]. In recent years, with the Pulse Width Modulation technology (PWM) applied in PHSV, the flow rate could be precisely controlled by adjusting the duty ratio [2]. The PHSVs are gradually replacing the servo valves or the proportional valves in precise displacement control [3-5], speed control [6], output force control [7], pressure control [8], etc. However, due to the lack of understanding and modeling of the dynamic and static flow rate of the PHSV, the control precision was not very high [3]. Therefore, the systematic study of flow characteristics and linearization is of great significance to the application and controller design.

At present, many scholars have studied the action characteristics, flow characteristics, dead zone compensation and linearization of PHSVs. Zhang Zhongxiang et al. [9] deeply analyzed the spool motion characteristics and provided a motion model within a control cycle, but did not continue to study the flow characteristics under such spool motion model. Xie Qi et al. [10] proposed a method of time interlaced modulation with four PHSVs, which could avoid the dead zone. Xiang Zhong et al. [11] proposed to replace the control chamber pressure delay characteristic with the spool motion delay characteristic, and studied the influence of control chamber volume and effective cross-sectional area on the characteristic of pressure delay. However, the dynamic flow characteristic was not studied to make further efforts. Xiaocong Zhu et al. [12] presented a simple linear relationship between the PWM signal duty ratio and flow rate. Meng Deyuan et al. [13] applied this relationship to the position control system. But this relationship was too simplified and ignored the opening and closing characteristics. R. Moreau et al. [14] designed a sliding mode controller to improve the dynamic flow fluctuation. Behrouz Najjari et al. [15] applied high voltage when opening the valve and reverse voltage when closing the valve to shorten the opening and closing delay and widen the flow linear interval. But this method could not completely eliminate the delay.
To sum up, there has not been a systematic and comprehensive study on the flow characteristics of PHSVs. In this paper, the static and dynamic characteristics are presented from the gas flow process and spool motion process, and a piecewise flow linearization method is discussed.

2. Static flow characteristics of high-speed on-off valve

At present, there are two kinds of PHSVs in the market: two-position two-way valve and two-position three-way valve. The latter can also be used as a two-position two-way valve by blocking one of the ports. Although there are some differences in the structure between the two (mainly affecting the switching frequency and flow rate range), they are consistent in the performance of flow characteristics. FESTO's MHE series valves are two-way three-way valves. As shown in the figure 1, when Port 3 is blocked, it can be used as a two-position two-way high-speed on-off valve. This valve would be tested and verified the theory on the static and dynamic flow characteristics of the PHSVs carried out in this paper. The model of the valve is MHE4-MS1H-3/2O-QS-8-K, the standard nominal flow rate is 400 L/min, and the maximum response frequency is 210 Hz.

The static flow characteristics of the PHSV refer to the relationship between the mass flow rate and the upstream and downstream pressures when the valve is fully open. As the orifice area is very small, the mathematical model of the gas flowing through the on-off valve in the pipeline can be simplified as that the gas flows through a contraction nozzle. Assuming that the gas is ideal, and the upstream volume is much larger than the downstream volume, it can be considered as one-dimensional isentropic flow. So the mass flow rate can be expressed as equation (1).

\[
q_m = \begin{cases} 
\frac{p_0 A_e}{R T_0} \left( \frac{2}{\kappa+1} \right)^{\frac{\kappa+1}{\kappa-1}} & \sigma \frac{p_0}{p_1} \leq 0.528 \\
\frac{2\kappa}{\kappa-1} \frac{1}{R T_0} \left( \sigma \right)^{\frac{2}{\kappa-1}} - \left( \sigma \right)^{\frac{\kappa+1}{\kappa-1}} & \sigma > 0.528
\end{cases}
\]

where: \( q_m \) – mass flow rate; \( A_e \) – cross-section area; \( \kappa \) – adiabatic index; \( R \) – gas constant; \( T \) – temperature, \( p \) – pressure, subscript 0 for upstream, subscript 1 for downstream, the same below. For air, \( \kappa = 1.4 \) \( R = 287 \text{ N m/(kg K)} \).

The MHE4 series valve instructions of FESTO company do not have the information cross-section area \( A_e \), and it is difficult to obtain the irregular valve port by direct measurement. The effective section area \( S_e \) can be measured by the sonic outgassing method, which can replace the physical area \( A_e \). According to the national standard GB / t14513-1993, the effective section area \( S_e = 9.10 \text{ mm}^2 \) following the steps in the national standard.

The flow measurement circuit was set up as shown in figure 2(a). The mass flow \( q_m \) was measured by keeping the outlet pressure at atmospheric pressure and adjusting the upstream pressure. The relationship between \( q_m \) and \( p_0/p_1 \) is illustrated in figure 2(b) that the test value is slightly larger than the theoretical value when the upstream pressure is large, and the error is about 4.5%. When the upstream pressure is small, the test value is slightly smaller than the theoretical value. This error may
be caused by the following reasons: 1. the accuracy of the flowmeter itself; 2. the simplification and assumption of the mathematical model; 3. the replacement of the effective section area. However, the range of error is very small, and the measured and theoretical value are in good agreement, so equation (1) can accurately describe the mathematical model of static flow characteristics through PHSV.

![Control signal diagram](image)

Figure 2 Static flow rate measurement

3. Dynamic flow characteristics of high speed on-off valve

3.1. Opening and closing characteristics

In an ideal state, assuming that the spool can act instantaneously under the driving of high and low pulse level, and there is no delay, the average section area per unit time can be calculated by equation (2) [13]. But in practice, because of the hysteresis of the solenoid coil and the delay of the spool motion, the opening and closing lag behind the pulse signal. To get the relationship between duty cycle $i$ and average flow rate $q_{ave}$ more accurately, it is necessary to analyze the opening and closing characteristics.

$$q_{ave} = A_{ave} \rho A_1 v_1 = A_1 \frac{T_{on}}{T_z} \rho A_1 v_1 = iq_{me}$$

where: $q_{ave}$ – average mass flow rate; $A_{ave}$ – average section area; $T_z$ – unit time; $T_{on}$ – high-level time; $i$ – duty;

Under the drive of the PWM signal, the movement process of the spool when the valve can completely open and close is as follows: 1. In the charging stage of the excitation coil, due to the inductance, the current gradually increases, and the electromagnetic force acting on the spool gradually increases. It takes $t_1$ to charge and overcome the friction force. 2. In the opening stage, the spool starts to move and it takes $t_2$. 3. During the complete opening stage, the coil is continuously powered on and the valve port is kept at the maximum opening. 4. In the discharging stage of the excitation coil, the current gradually decreases, but the electromagnetic force is still large enough to keep the maximum opening a period $t_3$. 5. In the closing stage, the electromagnetic force continues to decay, and it takes $t_4$ for spool back. Since the displacement of the spool is small and the movement time is short, assuming that the effective area changing is constant, the relationship between the opening degree and the control signal can be shown in figure 3.
Without destroying the valve, the coil charging time \( t_1 \), valve opening time \( t_2 \), coil discharging time \( t_3 \), and valve closing time \( t_4 \) can be obtained indirectly by measuring the current change in the coil [16]. These four critical times are measured and shown in Table 1.

### Table 1 Critical times

| \( t_1 \)  | \( t_2 \)  | \( t_3 \)  | \( t_4 \)  |
|---|---|---|---|
| 1.4ms | 1.6ms | 2.0ms | 1.5ms |

#### 3.2. Dynamic flow characteristics

The linear relationship between average flow rate and duty cycle in equation (2) is too simplified, which does not consider the situation that the valve cannot open or closed completely. Therefore, it is necessary to study the relationship between different control frequency and duty cycle with average flow rate to modify equation (2).

Define: average opening ratio \( r \) is the ratio of the integral of opening degree curve \( S(t) \) and the integral of maximum open degree \( S_c \) in a cycle. So the mass flow rate can be expressed as equation (3). Assuming that no matter what kind of motion state is in, once the valve is powered on or powered off, it will last for the opening time \( t_1 \) or closing time \( t_3 \).

\[
q_{av} = r q_m = \frac{\int_0^{T_a} S(t) \, dt}{\int_0^{T_a} S_c \, dt} \tag{3}
\]

1. \( 0 < T_m \leq t_1 \): The charging time is too short, and the spool would not move. The average opening ratio is 0.

2. \( t_1 \leq T_m < t_1 + t_2 \): The spool moves at the action of the electromagnetic force, but the high-level time is too short, the movement cannot be completed. The movement process is shown in figure 4(a), and the average opening ratio is expressed by equation (4).

\[
r = \frac{t_2 + t_1}{2t_1 f} (i - t_1 f) + \frac{t_1}{t_2} (i - t_1 f) \tag{4}
\]

3. \( t_1 + t_2 = T_m < t_1 - t_4 \): The valve can open and close completely. The movement process is shown in figure 3, and the average opening ratio is expressed by equation (5)

\[
r = i - f \left( t_1 + t_2 - t_3 - \frac{t_4}{2} \right) \tag{5}
\]

4. \( T_m - t_3 - t_4 < T_m < t_1 - t_4 \): The valve can be opened completely, but cannot be fully closed because the discharging time is short. The movement process is shown in figure 4(b), and its average opening ratio is expressed by equation (6)

\[
r = 1 - \frac{t_2 + t_1}{2t_1 f} (1 - i - t_1 f)^2 - \frac{t_4}{t_4} (1 - i - t_1 f) \tag{6}
\]
The valve is in the open state, and the average opening ratio is 1.

Figure 4 Incomplete opening and closing

Therefore, the relationship between the average flow rate and the duty cycle of the PWM signal can be expressed as equation (7), and its curve is shown in figure 5a. It is illustrated that the average flow rate is related to the frequency and duty cycle. At a certain frequency, if the duty cycle is too small, it will cause the opening dead zone of the on-off valve; if the duty cycle is too large, it will cause the closing dead zone of the on-off valve. There is a linear section. The ranges of the linear section and the dead zone are related to the frequency $f$: the smaller $f$, the smaller dead zone and the wider linear section would be. When the frequency is greater than $\frac{1}{(t_1 + t_2 + t_3 + t_4)}$, the linear segment disappears completely. Here, the opening and closing dead zone are collectively called the dead zone range, and the nonlinear segment and linear segment are collectively referred to as the adjustable range.

$$q_{av} = q_{in} \times \begin{cases} 0 & 0 < i \leq t_1 \\ \alpha(i-t_i f)^2 + \frac{t_2}{t_1}(i-t_i f) & t_1 < i \leq t_2 \\ 1 - \beta(1-i-t_i f)^2 - \frac{t_3}{t_4}(1-i-t_i f) & t_2 < i \leq t_3 \\ 1 & t_3 < i \leq 1 \end{cases}$$

(7)

where: $\alpha = \frac{t_2 + t_4}{2t_2 f}$; $\beta = \frac{t_2 + t_4}{2t_4 f}$; $t_1 = t_1 f$; $t_2 = (t_1 + t_2) f$; $t_3 = (t_3 + t_4) f$; $t_4 = 1 - t_3 f$

In order to verify the equation (7), experiments of the flow rate under PWM control with two frequencies, 80 Hz and 100 Hz, are carried out with the upstream pressure $p_0 = 0.4\text{MPa}$, downstream $p_1 = 0.1\text{MPa}$, duty cycle from 0% to 100%. The results are shown in figures 5(b) and 5(c). It can be seen that the dead zone, nonlinear segment, and linear segment are distinguished. When the control frequency is 100Hz, the range of dead zone and nonlinear segment is larger than that of 80Hz. Correspondingly, the range of linear segment with 100Hz control frequency is smaller than that with 80Hz. It can be considered that the average opening ratio $r$ can accurately reflect the average mass flow rate, and equation (7) can accurately describe the average flow rate under different duty ratios.
4. Linearization of dynamic flow rate

When designing a control system, researchers often expect the input and the actual output of the controlled object to present a linear relationship. For the PHSV, the average flow rate is required to be proportional to the control signal to simplify the control system. In the previous research, the control signal was directly equal to the duty cycle of the PWM signal. However, this method would cause the dead zone, or the control signal narrowed to avoid dead zone and nonlinear problems. In order to solve these problems, a piecewise indirect linearization method is proposed, which makes the flow rate linear in the whole range of system input.

According to the analysis in the previous section, the average opening ratio can accurately describe the relationship between the average flow, duty cycle, and frequency under the control of the PWM signal, and it is directly proportional to the flow rate. If the input \( u \) is proportional to the average opening ratio \( r \), the linear relationship between the average flow rate \( q_{\text{ave}} \) and the input \( u \) can be obtained. Thus, the relationship between duty cycle \( i \) and system input \( u \) should be calculated so that each input can correspond to a duty cycle and avoid the dead zone.

Firstly, the adjustable range of mass flow rate is extended from \( i \in [t_i, f, 1-t_i, f] \) to \( x \in [0, 1] \), and the abscissa needs to be transformed linearly \( i = [1-(t_i + t_f)] f x + t_i f \). After transformation, the equation (8) of the average opening ratio on \([0, 1]\) can be obtained

\[
r = \begin{cases} 
\frac{a \omega^2 x^2 + t_1 \omega x}{t_2} & 0 < x < X_1 \\
\frac{a \omega x - f \left(\frac{t_2}{2} - t_3 - \frac{t_4}{2}\right)}{1 - \beta a \omega^2 (1-x)^2} - \frac{t_2}{t_4} & X_1 < x < X_2 \\
1 - \beta a \omega^2 (1-x)^2 & X_3 < x < 1 
\end{cases}
\]

where: \( \omega = 1 - (t_i + t_f) f \); \( X_1 = \frac{t_i f}{1 - (t_i + t_f) f} \); \( X_2 = \frac{1 - (t_i + t_f) f}{1 - (t_i + t_f) f} \).

Generally, the input range is a continuous interval. To simplify the derivation and calculation, it is normalized to the unit interval \([0, 1]\). Then the proportional relationship between \( u \) and \( r \) can be defined as \( u = r \), and equation (9) is obtained.
The relationship between the average flow rate and input is $q_{ave} = u q_m$.

At this time, the relationship between the average flow rate and input is $q_{ave} = u q_m$.

The principle can be shown in figure 6. For a certain frequency, each system input $u$ would calculate a corresponding duty ratio $i$ through equation (9) to control the PHSV. The average flow rate $q_{ave}$ is proportional to the system input $u$.

5. Conclusion

In this paper, the pneumatic high-speed on-off valve is taken as the research object, and the static and dynamic flow characteristics are systematically studied. After fully studying the spool action, the average opening ratio is proposed to reflect the change of average flow rate under PWM signal control. This method can accurately reflect the dead zone, nonlinear characteristics, and the relationship with frequency and duty cycle. The experimental results show that the method is accurate and effective, and the error between theoretical calculation and the actual measurement is small.

A piecewise indirect linearization method is proposed. Under a certain frequency, the duty cycle is calculated corresponding to an input, to control the valve. So that the system input and the average flow rate are indirectly linear.

References

[1] Saravanakumar D., Mohan B., and Muthuramalingam T. (2017) A review on recent research trends in servo pneumatic positioning systems. Precision Engineering, 49:481-492.

[2] Wang W., Song J., Li L., Li H., High speed on-off solenoid valve with proportional control based on high frequency PWM control, (2011) J Tsinghua Univ (Sci & Tech), 51:715-719 (in Chinese)

[3] Guo Y., Jin A., Wang J., et al., (2017) Research on cylinder servo system of loading and unloading manipulator under the control of high-speed switching valve, Journal of Hefei University of Technology, 40:154-158 (in Chinese)

[4] Moezi S. A., Rafeeyan M., Zakeri E., Zare A. (2016) Simulation and experimental control of a 3-RPR parallel robot using optimal fuzzy controller and fast on/off solenoid valves based on the PWM wave. Isa Transactions, 61:265-286.
[5] Xie S., Liu H., Mei J., et al. (2017) Simulation of Tracking Control of Pneumatic Artificial Muscle Based on Fast Switching Valves, Transactions of the Chinese Society for Agricultural Machinery, 48:368-374 (in Chinese)

[6] Ji R., Lin Z., Wei Q., et al. (2020) Research on Servo Force Control System for Pneumatic Cylinder Based on On-off Valves, Hydmulics Pneumatics & Seals, 04:12-18 (in Chinese)

[7] Wang J., Gordon T. (2012) Energy optimal control of Servo-Pneumatic cylinders through nonlinear static feedback linearization [J]. Journal of Dynamic Systems, Measurement, and Control, 134:51005.

[8] Tang L., Han J., Zhao S., et al. (2009) Precision Control of Air Pressure Based on Micro-Adjusting Using High-Speed ON/OFF Valves, Chinese Hydraulics & Pneumatics, 9:9-11. (in Chinese)

[9] Zhang Z., Liu Z., (2007) Model and control method research of high speed on-off valve, Electrotechnical Application, 11:88-90 (in Chinese)

[10] Xie Q., Lin Z., Zhang T., (2019) Research on pneumatic servo position control system based on time interlaced modulation with four on-off valves. Hydmulics Pneumatics & Seals 39:19-25 (in Chinese)

[11] Xiang Z., Tao G., Xie J., et al. (2008) Simulation and experimental investigation on pressure dynamics of pneumatic high-speed on/off valves, Journal of Zhejiang University (Engineering Science) 42:845-849 (in Chinese)

[12] Zhu X., Meng D., Tao G. (2014) Adaptive Robust Motion Trajectory Tracking Control of Pneumatic Cylinders with LuGre Model-based Friction Compensation. Chinese Journal of Mechanical Engineering, 27:802-815.

[13] Meng D., Tao G., Li A., Li W., (2015) Adaptive Robust Control of Pneumatic Cylinders Using Fast Switching on/off Solenoid Valves, Journal of mechanical engineering, 51:180-188 (in Chinese)

[14] Moreau R., Pham M. T., Tavakoli M., et al. (2012) Sliding-mode bilateral teleoperation control design for master-slave pneumatic servo systems. Control Engineering Practice, 20(6):584-597.

[15] Najjari B., Barakati S. M., Mohammadi A., et al. (2014) Position control of an electro-pneumatic system based on PWM technique and FLC. Isa Transactions, 53(2):647-657.

[16] Dong D., Li X., (2015) Development of a novel parallel-spool pilot operated high-pressure solenoid valve with high flow rate and high speed. Chinese Journal of Mechanical Engineering, 28(2):369-378.