# Reducing the Limit Cycle Oscillation of a Full-Digital Pneumatic Motor Speed Control System

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### Abstract

In this paper, an improved full-digital closed-loop pneumatic motor speed control system with reduced limit cycle oscillation is developed and realized. A significant feature of the proposed structure is the combination of the proportional technology as well as the full-digital control scheme. The utilized proportional full-digital control valve (FDCV) consists of four parallel-connected 2/2 pneumatic on-off valves with multiple flow-rate outputs. Compared to the PWM flow control scheme using four fast-switching 2/2 on-off valves, the proposed FDCV possesses several advantages like medium operating noise, long life, ease of control and low cost. The simple but effective binary coding system is chosen for this study. The major fault of the conventional FDCV, however, is its nonlinear saw-toothed flow-rate characteristic which generally results in the undesirable limit-cycle oscillation in the steady-state response. Therefore, a novel technique to reduce the amplitude of limit-cycle oscillation is developed in this paper. The basic idea is to reduce the opening areas of four on-off valves in the FDCV simultaneously by applying lower current inputs to the valve coils in the steady-state. Consequently, the limit cycle oscillation of the pneumatic motor speed control can be successfully reduced without any hardware modification. Finally, experiment results prove that the amplitude of the steady-state limit cycle oscillation is significantly reduced by using the proposed two-step current switching controller. Therefore, the FDCV together with the proposed novel current switching control strategy is a potential alternative of precise closed-loop pneumatic motor speed control.

KEYWORDS: full-digital control, pneumatics, pneumatic motor, variable current technology

#### 1. Introduction

In a conventional servo-pneumatic motor speed control system, servo valve or proportional valve is generally utilized to achieve linear and continuously variable speed control. However, such valves are generally very expensive and they are analogue components that are sensitive to external noise or disturbance. To reduce the cost, another digital proportional control structure is proposed /2/, in which four or more fast-switching 2/2 on-off valves using PWM-control are employed. A significant advantage of the fast-switching PWM-control scheme is the lower cost. Its major faults, however, are noisy operation, short life and the obvious steady-state error. In this paper, therefore, an improved full-digital proportional pneumatic motor speed control system is developed and realized /7, 8/. The presented full-digital control valve (FDCV) consists of four parallel-connected 2/2 pneumatic on-off valves. In addition, a SSR relay module and the binary coding system are also necessary components. Compared to the conventional PWM-control fast-switching proportional flow control structure, the proposed full-digital control system possesses several advantages like low operating noise, long life and ease of control. Similar to the simple sequence control structure, the basic operating principle of the FDCV is that the number of actuated 2/2 pneumatic on-off valves depends on the actual demand of the air flow-rate. In details, if the demanded air flow-rate is quite low, then only few on-off valves with smaller flow-rate output will be energized to supply small amount of airflow to the system. On the other hand, if the speed control system demands larger air flow-rate, then more 2/2 on-off valves with larger flow-rate output will be switched to ON position. Table 1 shows the comparisons between aforementioned three control structures.

Surveying some previous reports, it can be found that the concept of full-digital control scheme proposed in this paper can be found in early 1980s /1/. However, this control scheme was not considered to be promising because the global digital revolution just began and was not fully developed at that time. On the other hand, the commercial products of 2/2 pneumatic on-off valve in 1980s were generally slow, expensive and bulky, which were definitely not suitable for the realization of the full-digital proportional pneumatic speed control system. Nowadays, however, the digital revolution covers all fields of technology, entertainment and other aspects. In addition, some fast, low-cost and small-sized sectional 2/2 pneumatic on-off valves are developed and commercialized. Thus, it may be concluded that the full-digital control scheme is ready for the application to pneumatic motor control systems. However, the major fault of the FDCV is its nonlinear saw-toothed flow-rate characteristic which generally results in the limit-cycle oscillation and the undesirable steady-state error. Therefore, a novel

technique to reduce the steady-state error is further developed in this paper. A significant feature of the proposed structure is the combination of the proportional technology as well as the conventional full-digital control scheme as shown in Fig. 1. The basic idea of the proposed novel technique is to adjust the opening areas of all four on-off valves in the FDCV by applying two-step current input scheme to the valve coils. Consequently, without any hardware modification, an alternative saw-toothed flow-rate characteristic with higher resolution but less maximal flow-rate is available in the steady-state response if the lower current is applied to the solenoid valve coils. In details, after reaching the pre-set quasi steady-state response, the control scheme is then switched from the larger maximal flow-rate mode to the higher resolution mode so that the steady-state error arising from the limit-cycle oscillation can be effectively reduced. In the following, the coding system as well as the designed test bench for the full-digital pneumatic motor speed control is outlined.

	Full-digital proportional control	PWM fast- switching on/off control	Traditional proportional/ servo valve control
Cost	Medium	Low	High
Life	Long	Short	Long
Noise	Medium	High	Low
Dimension	Medium	Small	Small

Table 1: The co	omparisons betweer	aforementioned t	hree control schemes.
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Figure 1: Key novelty of the proposed control strategy.

## 2. Coding System and Test Bench

In this paper, the simple but effective binary coding system is utilized /3, 4/. Figure 2 shows the details of the binary coding system. The nonlinear and discontinuous saw-toothed air flow-rate output is depicted in Fig. 3. Obviously, the binary coding system requires four 2/2 on-off valves with different but multiple flow-rate outputs (1Q, 2Q, 4Q and 8Q). In addition, to achieve the synchronous actuation of the valves, it is essential that all four 2/2 on-off valves are of the same type and manufactured by the same

company. In real implementation, however, it is further suggested that four additional simple flow control valves are utilized to precisely adjust the multiple air flow-rate outputs as shown in Fig. 4. Figure 5 shows the real picture of the designed FDCV consisting of four 2/2 pneumatic on-off valves and the circuit diagram of the full-digital pneumatic motor speed control system is shown in Fig. 6. Obviously, the speed of the pneumatic motor can be controlled by only one FDCV, which meters the air flow-rate output for P->A position. In the beginning, the FDCV is fully opened. Thus, the pneumatic motor is accelerated. However, if the motor runs too fast meaning that the control overshoot occurs, the FDCV is then switched off and the motor slows down gradually due to inertia and friction force. To measure the speed of the pneumatic motor, a simple digital encoder is utilized. The measured speed signal is then fed-back to the PC-based controller to form a closed-loop control scheme. In addition, a SSR module consisting of four solid-state relays and a voltage-to-current transducer serve as the main driver unit in the test device.

Due to the discontinuous saw-toothed air flow-rate characteristic shown in Fig. 3, the limit-cycle oscillation is generally inevitable and exists in the steady-state response /8/. This is chiefly because that one or two 2/2 on-off valves of FDCV are still switched on and off continuously trying to reduce the steady-state error in the closed-loop steadystate response. Surveying some previous relevant studies, it is found that different coding systems in full-digital control structure can be used to reduce steady-state error /3, 4/. In this paper, however, a simple but novel full-digital current switching control strategy based on conventional binary coding system is proposed to reduce the amplitude of the undesired limit-cycle oscillation. Referring to the force/stroke family curves of a general switching solenoid as shown in Fig. 7, it is clear that different force output can be obtained if the input current is changed. An example is also given in Fig. 7. That is, if the input current is changed from  $i_1$  to  $i_2$ , then the spool/poppet stroke of the on-off value is varied from  $S_1$  to  $S_2$ . Therefore, the opening area and the air flowrate output of the on-off valve will also be changed accordingly. In summary, the basic idea of the proposed current switching control structure is to reduce the opening areas of four 2/2 on-off valves in the FDCV simultaneously by applying lower input excitation current to the coils. Consequently, in the steady-state response, an alternative sawtoothed flow-rate with higher resolution but less maximal flow-rate is available as shown in Fig. 8. The most suitable switching timing has to be obtained by trial-anderror and is found to be the time when the transient response reaches around 50 % of its final value for the tested pneumatic motor. This is also defined as the beginning of the quasi steady-state response in this paper. At this moment, the control scheme is switched from high speed mode to high resolution mode so that the steady-state error is expected to be reduced effectively.

Binary FDCV							
Net Flow	Valve1, 1Q	Valve2, 2Q	Valve3, 4Q	Valve4, 8Q	State		
0	0	0	0	0	0		
1Q	1	0	0	0	1		
2Q	0	1	0	0	2		
3Q	1	1	0	0	3		
4Q	0	0	1	0	4		
5Q	1	0	1	0	5		
6Q	0	1	1	0	6		
7Q	1	1	1	0	7		
8Q	0	0	0	1	8		
9Q	1	0	0	1	9		
10Q	0	1	0	1	10		
11Q	1	1	0	1	11		
12Q	0	0	1	1	12		
13Q	1	0	1	1	13		
14Q	0	1	1	1	14		
15Q	1	1	1	1	15		

Figure 2: Details of the binary coding system.



Figure 3: Discontinuous saw-toothed air flow-rate.



Figure 4: Symbol for the binary-coding FDCV.



Figure 5: The picture of designed FDCV.



Figure 6: Proposed circuit diagram of the Full-Digital pneumatic motor speed control system.



Figure 7: Force/stroke family curves of a general switching solenoid.



**Figure 8:** Comparison between the discontinuous air flow-rate output for high speed mode and high resolution mode.

### 3. Novel Two-Step Current Controller Design

Figure 9 shows the block diagram of the closed-loop motor speed control system. To show the validation of the proposed full-digital proportional pneumatic motor speed control scheme, a simple PID controller is utilized in this paper as shown in Eq. (1). The chosen gains for the PID controller are also obtained by trial-and-error approach. As shown in Fig. 9, it is observed that the first-step current input (0.7A) is supplied to the on-off valves if the actual motor speed,  $\omega$ , is lower than the pre-set switching timing, for example,  $\omega < 0.5R$ , where the symbol R denotes the desired speed input to the system. At this moment, the metering areas of all four on-off valves are fully opened resulting in maximal airflow-rate output to achieve fastest response. Therefore, it is called the high-speed mode in this paper. On the other hand, if the motor speed exceeds the pre-set switching timing, for example,  $\omega > 0.5R$ , the input current is then switched to the second-step current (0.3A). At this moment, the opening areas of four on-off valves are

reduced. This is called the high-resolution mode. Meanwhile, the air flow-rate output is also reduced by nearly 35%.

Figure 9: Block diagram of the novel full-digital closed-loop speed control system.

#### 4. Experimental results of the motor speed control and discussion

Owing to the nonlinear saw-toothed airflow-rate characteristic shown in Fig. 3, it can be seen that the air flow-rate output between 0 and 1Q (for example: 0.65Q) is practically impossible due to the inherently poor resolution of the full-digital control system. Consequently, the limit-cycle oscillation is inevitable and exists in the steady-state response because one or two 2/2 on-off valves of FDCV are still switched on and off continuously trying to reduce the steady-state error in the closed-loop steady-state response. In this paper, a novel current switching control strategy is proposed that makes the higher resolution of air flow-rate possible. In details, the original 16-step resolution of the saw-toothed air flow-rate shown in Fig. 3 can be theoretically doubled by switching the input current between the normal (+24V, 0.7A) and the smaller current value (+24V, 0.3A). In this paper, the former is named the first-step current and the latter is called the second-step current. Consequently, the value of the parameter K in Fig. 7 is found to be 0.65 approximately and the air flow-rate output of 0.65Q becomes possible. Figure 10 shows the open loop speed control performance of the tested pneumatic motor. There are two curves in this figure. The upper curve represents the motor speed output using the first-step input current (0.7A) and the lower curve indicates the motor speed output using the second-step input current (0.3A). Obviously, the resolution is increased from 16 steps to the theoretical 31 steps without any hardware modification if both current levels are switched properly. However, it is also noticeable that two kinds of nonlinearity, that is the dead-zone and saturation, exist in the open loop speed control performance. Such nonlinearities can be effectively compensated by the closed-loop control scheme. Figure 11 shows the closed-loop

motor speed control responses. The desired motor speed input is set to be 750 rpm. From the enlarged response curves shown in Fig. 12, it is observed that the limit-cycle oscillation exists. To quantify the steady-state error, the root-mean-square method is chosen. After some calculations, the root-mean-square steady-state error is decreased from 30 rpm to 5 rpm if the proposed two-step current switching control scheme is utilized. That is, the steady-state error is decreased by nearly 80%. The PID controller gains for the experiments are chosen to be  $K_P = 7.2V/rmp$ ,  $K_I = 0.002 V^*s/rpm$  and  $K_D = 0.03 V^*s^2/rpm$  respectively and the switching timing is set to be 50%. However, the proposed full-digital two-step current switching control scheme introduces inevitably some phase lag in the transient response. This is reasonable because the maximal flow-rate output is reduced by 35% when the high resolution mode is switched on.



Figure 10: Open loop speed control performance of the tested pneumatic motor between the first-step current input and the second-step current input.



Figure 11: Experimental comparison between the conventional binary coding controller and the proposed full-digital two-step current switching controller (Switching timing: 50%).



Figure 12: Enlarged comparison between 600 rpm and 1000 rpm.

## 5. Conclusion

In this paper, a novel full-digital control with two-step current switching scheme for the pneumatic motor speed control system is successfully developed and implemented. It is proved experimentally that the amplitude of the steady-state limit-cycle oscillation is significantly reduced by using the proposed two-step current switching control as compared to the utilization of a conventional full-digital control scheme. One possible future work is to extend the two-step current switching to multi-step or even continuous current switching. Therefore, it is expected that such a novel FDCV with current

switching scheme has the potential to replace some traditional proportional or servo valves in the future.

## 6. Acknowledgement

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## 8. Nomenclature

u(k)	actuating signal	rpm
e(k)	error signal	rpm
$K_P$	gain of the proportional controller	V/rpm
K <sub>I</sub>	gain of the integral controller	V*s/rpm
$K_D$	gain of the derivative controller	V*s²rpm