# A Study on Energy Saving Algorithm of Electro-Pneumatic Regulator with Modified PWM Driven Method

**Hyoung-Seok Kim, Kyoung-Kwan Ahn*, Byung-Ryong Lee**
*School of Mechanical and Automotive Engineering, University of Ulsan, San 29, Muger 2-dong, Nam-gu, Ulsan 680-749, Korea*
**So-Nam Yun**
*Korea Institute of Machinery & Materials*

The development of an accurate and energy saving electro-pneumatic regulator that may be applied to a variety of practical pressure control applications is described in this paper. A novel modified pulse width modulation (MPWM) valve pulsing algorithm allows the electro-pneumatic regulator to become energy saving system. A comparison between the system response of conventional PWM algorithm and that of the modified PWM (MPWM) algorithm shows that the control performance is almost the same, but energy saving is greatly improved by adopting this new MPWM algorithm. The effectiveness of the proposed control algorithm is demonstrated through experiments with various reference trajectories.

**Key Words :** Electro-Pneumatic, On/Off Solenoid Valve, Pressure Control, PID Control, MPWM

## 1. Introduction

Pneumatic actuators offer the following advantages : low cost, high power-to-weight ratio, ease of maintenance, cleanliness, a readily available and cheap power source. Therefore the pneumatic actuator is the most popular actuator in control of robot manipulator, end effectors and where stiff and lightweight structures. Unfortunately, the difficulty in pneumatic actuator control comes from the high compressibility of air and high friction (Ahn et al., 2005 ; Ahn, 2004 ; Robert et al., 1997 ; Ning et al., 1991). And also in such systems, the cost of the servovalve in nearly all cases dominates the cost of the actuator. Pulse width modulated (PWM) control offers the ability to provide servocontrol of pneumatic actuators at a significantly lower cost by utilizing on/off solenoid valves in place of costly servovalves (Shen et al., 2004). Huu (1987) and Hwang et al. (1998) controlled the displacement using a pneumatic servo valve and Kimura et al. (1995) showed that feedback linearization method with step-type disturbance rejection has been applied to control pneumatic actuator with static friction. Wang and Peng (2003) studied the dynamic modeling and motion control of pneumatic manipulator using dynamic neural network. Wang et al. (1999) developed a control strategy based on a PID controller with acceleration feedback and nonlinear compensation for servo pneumatic actuator system. Lee (1985) effectively controlled an on/off valve using PI controller and PWM driving method. Cho and Lee (1985) proposed the deadband and pulseband of modified on/off controller with PD control and studied the pulse modulated value and pulse band ratio. However, most of the conventional studies are about the position control,

* Corresponding Author,
**E-mail** : kkahn@ulsan.ac.kr
**TEL** : +82-52-259-2282; **FAX** : +82-52-259-1680
School of Mechanical and Automotive Engineering, University of Ulsan, San 29, Muger 2-dong, Nam-gu, Ulsan 680-764, Korea. (Manuscript **Received** July 15, 2005; **Revised** June 1, 2006)

and little research work about pressure control has been reported up to now. Most of the conventional pressure control valves in the pneumatic systems are not appropriate for accurate pressure control because their working is done by on/off operation. In other words, on/off operation is difficult to control the system pressure proportionally because only on/off operation is possible when we use this system.

This paper proposes a novel modified pulse width modulation (MPWM) valve pulsing algorithm for improving the accuracy of pressure control and the energy saving of electro-pneumatic regulator, and investigate the effectiveness of the proposed MPWM by experiments.

## 2. Proposition of Modified PWM Algorithm

### 2.1 Structure of the electro-pneumatic pressure regulator

Electro-pneumatic regulator, which is shown in Fig. 1 can control system pressure proportionally. This regulator consists of controller, air supply solenoid valve and exhaust solenoid valve, exhaust and supply valve, pressure sensor and diaphragm.

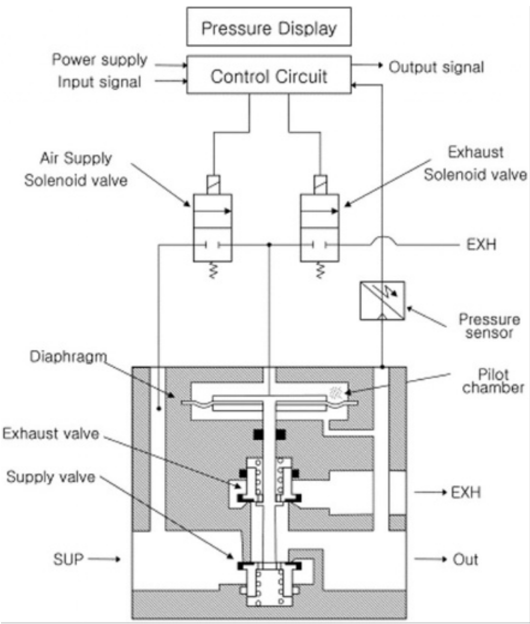


**Fig. 1** System configuration

Figure 2 shows the basic control block diagram which is composed of PID controller, PWM modulator with saturation function, electro-pneumatic regulator. PID controller for pressure control of electro-pneumatic regulator is represented by the following equation.

$$V = K_p \cdot (P_d - P) - K_d \cdot \frac{d(P_d - P)}{dt} + K_i \cdot \int (P_d - P)\,dt \tag{1}$$

$V$ : Control Input $\quad$ $P_d$ : Desired Pressure
$P$ : System Pressure $\quad$ $K_p$ : Proportional Gain
$K_i$ : Integral Gain $\quad$ $K_d$ : Derivative Gain
$t$ : Continuous Time

The control input value '$V$' is calculated by the PID controller and it is converted to PWM output by saturation function. The pressure of electro-pneumatic regulator is controlled by driving solenoid valves according to the PWM output

Figure 3 shows the change of pulse width time with respect to the duty ratio. Here $U_{PWM}$, $U_0$, $U(k)$, $U_{\max}$, $k$ and $T$ denote PWM output voltage, applied voltage for opening solenoid valve, output of saturation function, maximum value of saturation function, discrete time and a cycle time of PWM, respectively. Here the opening time of

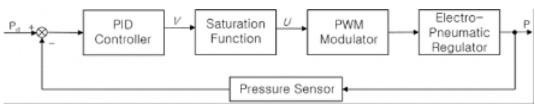


**Fig. 2** Basic control block diagram

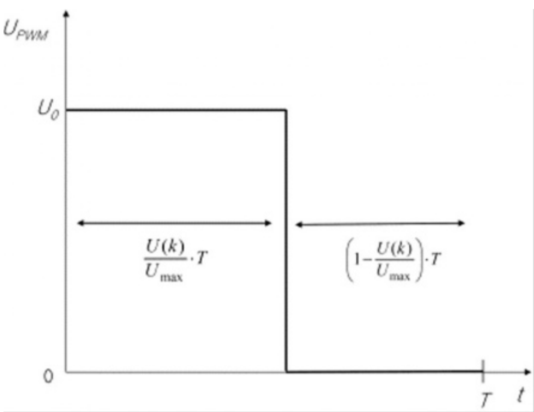


**Fig. 3** Duty ratio of PWM algorithm

solenoid valve becomes $T$, if $U(k)$ is larger than $U_{\max}$.

### 2.2 Conventional PWM algorithm

While conventional pressure regulator is difficult to control the pressure proportionally. The pressure of electro-pneumatic regulator is proportionally controlled by adjusting the opening time of solenoid valve which is shown in Fig. 4. The opening time of solenoid valve is adjusted by the output of saturation function. Saturation function limits the PID control value between 0 and 1.

Hyperbolic tangent sigmoid function is used as a saturation function and is represented by the following equation.

$$U(k)=\frac{1}{1+e^{-V(k)}} \tag{2}$$

Here $V(k)$ is discrete value of PID control output. In this case, $U_{\max}$ becomes 1 and the opening time of the solenoid valve for a cycle is determined by the multiplication of $u(k)$ and cycle time $T$. The algorithm for calculating pulse width time of solenoid valve is represented by the following expression.

$$\begin{aligned} U_{PWM}&=\begin{cases} U_0 & 0\le t\le t_p(kT) \\ 0 & t_p(kT)<t\le T \end{cases} \\ t_p(KT)&=\frac{U(k)}{U_{\max}}\cdot T \end{aligned} \tag{3}$$

$t_p$ : Opening time of the solenoid valve for a cycle

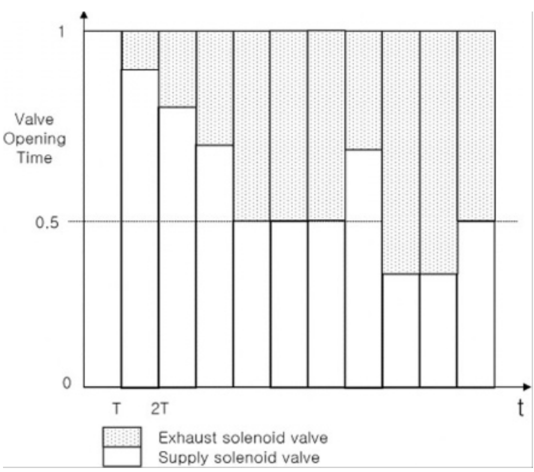


**Fig. 4** Valve opening time by conventional PWM

For example, the opening time of air supply solenoid valve is $0.6T$ if the output of saturation function is 0.6 and the opening time of exhaust solenoid valve is $(1-0.6)T=0.4T$ in that time. However, a lot of energy is wasted by the above-mentioned algorithm because the total operation time of air apply and exhaust solenoid valves always becomes a cycle time for a cycle even if the system pressure reaches the desired pressure.

### 2.3 The modified PWM algorithm for energy saving

A conventional PWM algorithm has the advantage of rapidly reaching the desired pressure but energy consumption is large. Therefore, a new algorithm is proposed for the propose of energy saving and improvement of the control performance. Figure 5 shows the valve opening time by the proposed PWM algorithm.

Here, modified hyperbolic tangent sigmoid function is used as saturation function, which is represented as the following equation.

$$U(k)=\frac{2}{1+e^{-V(k)}}-1 \tag{4}$$

The output of saturation function has the range from '$-1$' to '1'. If the sign of saturation function output is '+', just air supply solenoid valve is operated and exhaust solenoid valve is operated if the sign of saturation function output is '$-$'. Equation (5) shows the algorithm calculating the opening time of solenoid valve.

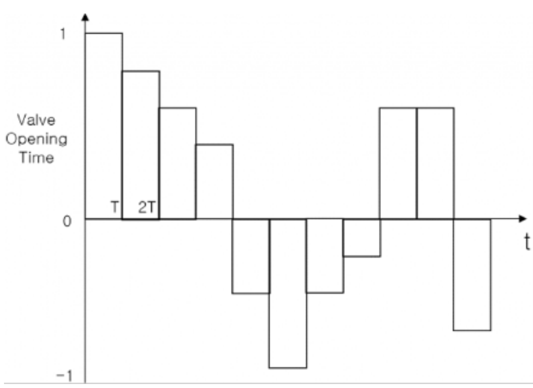


**Fig. 5** Valve opening time by proposed PWM

$$
\begin{aligned}
&U_{PWM\_IN}(t)=\begin{cases} U_0 & (k-1)T \le t \le (k-1)T+t_{p1}(k) \\ 0 & (k-1)T+t_{p1}(k) \le t < kT \end{cases} \\
&t_{p1}(k)=\begin{cases} \dfrac{U(k)}{U_{\max}}\cdot T & U(k)>0 \\ 0 & U(k)<0 \end{cases} \\
&U_{PWM\_EX}(t)=\begin{cases} U_0 & (k-1)T \le t \le (k-1)T+t_{p2}(k) \\ 0 & (k-1)T+t_{p2}(k) \le t < kT \end{cases} \\
&t_{p2}(k)=\begin{cases} 0 & U(k)>0 \\ \dfrac{|U(k)|}{U_{\max}}\cdot T & U(k)<0 \end{cases}
\end{aligned} \tag{5}
$$

$U_{PWM\_IN}$ : PWM Output Voltage of Air Supply Solenoid Valve

$U_{PWM\_EX}$ : PWM Output Voltage of Exhaust Solenoid Valve

For instance, the opening time of air supply solenoid valve is $0.6T$ if the output of saturation function is 0.6 and exhaust solenoid valve are always closed. Conversely, the opening time of exhaust solenoid valve is $0.6T$ if the output of saturation function is $-0.6$ and air supply solenoid valve are always closed.

## 3. Experiments

In this experiment, a conventional PWM and the proposed PWM driven method are applied for the pressure control of electro-pneumatic regulator. The performance of pressure control is compared and examined. $T$ is 10 ms in all experiments. Figure 6 shows the experimental results of the sine response and the control input, which can be seen in PID value, by the conventional PWM driven method. The maximum tracking error is 0.022 MPa. Figure 7 shows the experimental results of the sine response and the control input, which can be seen in PID value, by the proposed PWM driven method. The maximum tracking error is 0.012 MPa. The results of experiments show that the tracking performance is almost the same.

Figure 8 shows the experimental results of the increasing step response and the control input, which can be seen in PID value, by the conventional PWM driven method. The rising time, overshoot, steady state error is 0.04 sec, 13.9%,

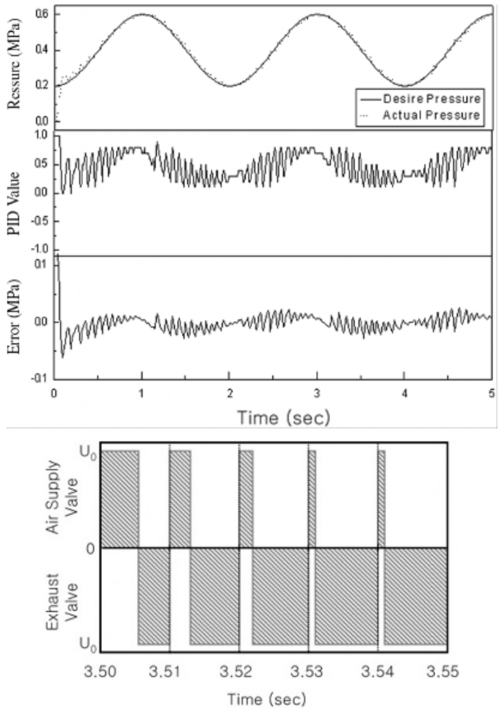


**Fig. 6** Experimental results of sine response by conventional PWM

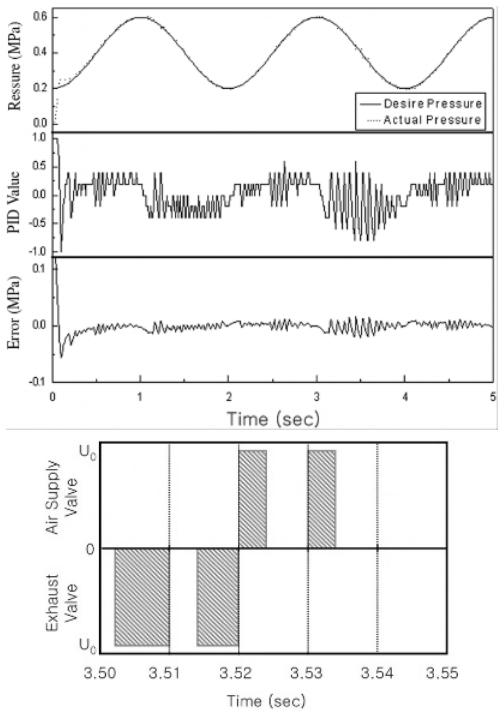


**Fig. 7** Experimental results of sine response by proposed PWM

0.002 MPa respectively. Figure 9 shows the experimental results of the increasing step response and the control input, which can be seen in PID value, by the proposed PWM driven method. The rising time, overshoot, steady state error is 0.04 sec, 14.9%, 0.002 MPa respectively.

Figure 10 shows the comparison of valve opening time between the result of Fig. 8 and result of Fig. 9. The opening time of air supply solenoid valve is represented by the upper part in the figure and the opening time of exhaust solenoid valve is represented by the lower part in the figure. The opening time of solenoid valve is proportional to the width of the rectangle with oblique lines. In the conventional PWM algorithm, both of the air supply and exhaust solenoid valve are operated 5 times but the air supply and exhaust solenoid valve are operated 3 times and 1 time respectively by using the proposed PWM algorithm. If the consumption of electric energy is assumed to be proportioned to the opening time of solenoid valves, the consumption of electric energy is said to be reduced 63% than a conventional PWM algorithm.

Figure 11 shows the experimental results of the decreasing step response and the control input, which can be seen in PID value, by the conventional PWM driven method. The rising time, overshoot, steady state error is 0.06 sec, 3.6%,

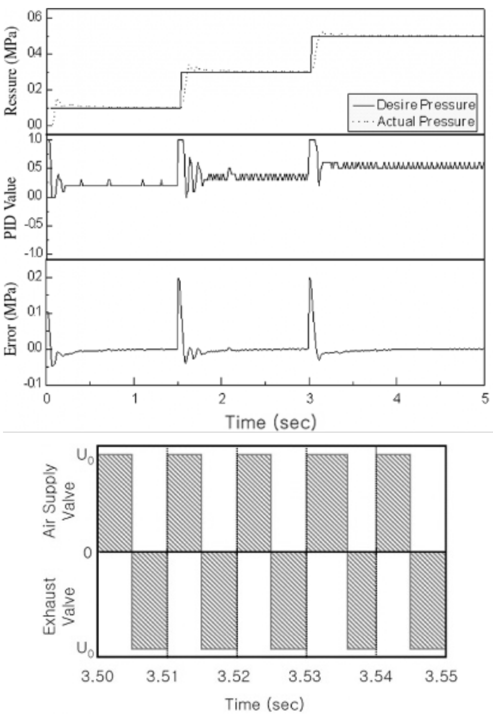


**Fig. 8** Experimental results of increasing step response by conventional PWM

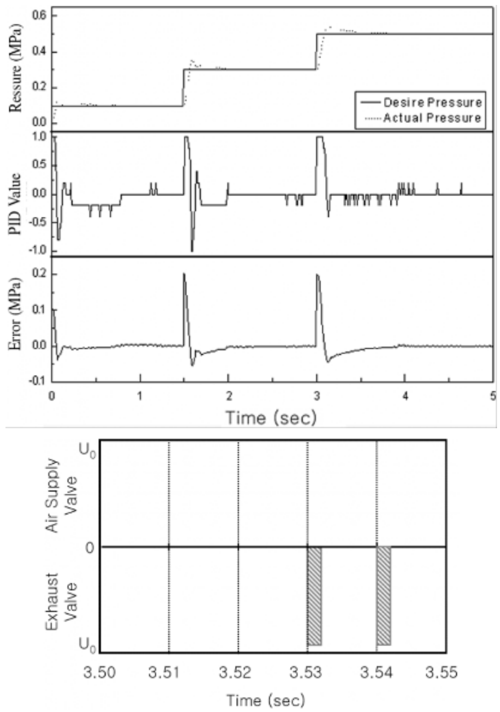


**Fig. 9** Experimental results of increasing step response by proposed PWM

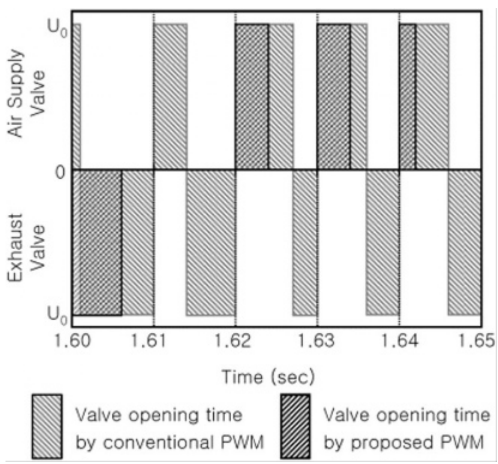


**Fig. 10** Comparison of valve opening time

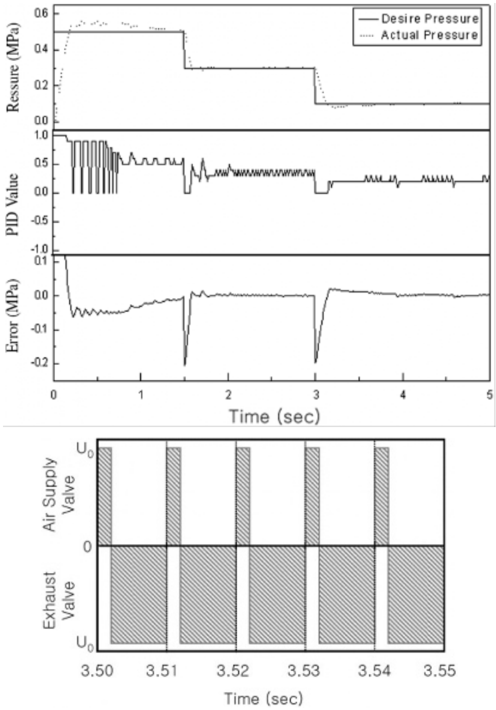


**Fig. 11** Experimental results of decreasing step response by conventional PWM

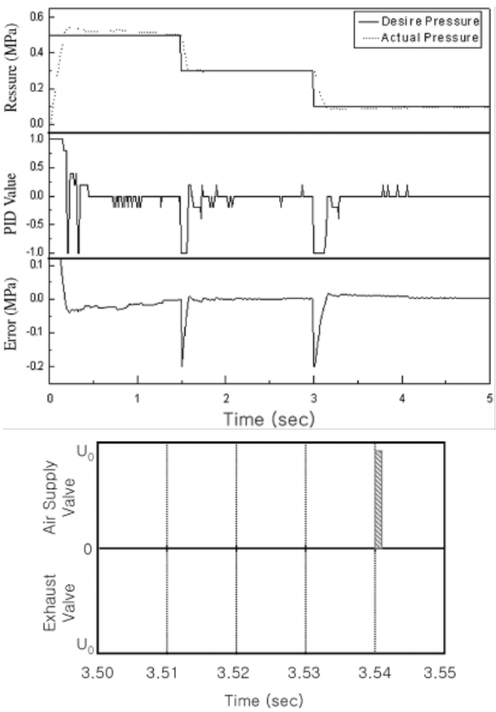


**Fig. 12** Experimental results of decreasing step response by proposed PWM

0.004 MPa respectively. Figure 12 shows the experimental results of the decreasing step response and the control input, which can be seen in PID value, by the proposed PWM driven method. The rising time, overshoot, steady state error is 0.05 sec, 2.5%, 0.003 MPa respectively.

## 4. Conclusions

A on/off driven type conventional pneumatic valve is difficult to control the system pressure proportionally and a conventional PWM driven method has a problem of large energy consumption although it has good tracking performance.

In this paper, a modified PWM algorithm is proposed for the control of pressure of electro-pneumatic regulator. The proposed PWM algorithm is verified to have almost the same tracking performance with the conventional algorithm as well as save energy through the experiments of sinusoidal and step response. The proposed PWM algorithm operates the air supply solenoid valve when the sign of PID controller output is positive and it operates the exhaust solenoid valve when sign of PID controller output is negative. That is, the consumption of electric energy can be reduced significantly with the proposed PWM algorithm.

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## References

Ahn, K. K. and Tu, D. C. T., 2004, "Improvement of the Control Performance of Pneumatic Artificial Manipulators Using an Intelligent Switching Control Method," in *KSME*, Int. Jour., Vol. 18, No. 8, pp. 1388～1400.

Ahn, K. K., Tu, D. C. T. and Ahn, Y. K., 2005, "Performance Improvement of Pneumatic Artificial Muscle Manipulators Using Magneto-Rheological Brake," in *KSME*, Int. Jour., Vol. 19, No. 3, pp. 777～790.

Cho, H. S. and Lee, C. W., 1985, "Perfomance of a Modified On-off Controller with PD action of Pneumatic Servomechanism," Int. Sym. on *Fluid Control and Measurement*, Tokyo, Sept, pp. 37～45.

Huu, T. N., 1987, "Verhalten servopneumatischer Zylinderantriebe im Lageregelkreis," Ph. D. thesis, Rety-Aachen.

Hwang, W. T., Choi, S. H. and Lee, J. O., 1998, "Study on the Effective Operating Method of the on-off Valve for a Pneumatic Servo System," *KSPE*, Vol. 15, No. 1.

Kimura, Tetsuya et al., 1995, "Control for pneumatic Actuator Systems using Feedback Linearization with Disturbance Rejection," Proc. of the 1995 *American Control Conf*., June, pp. 825～829.

Lee, S. G., 1985, "On the Development of a PWM Control-based Pneumatic Servomechanism," Int. Sym. on *Fluid Control and Measurement*, Tokyo, Sept., pp. 29～36.

Ning, Ye. et al., 1991, "A Servocontrolled Pneumatic Actuator for Small Movement Application to an Adaptive Gripper," *IEEE*.

Robert, B. van Varseveld and Gary, M. Bone, 1997, "Accurate Position Control of a Pneumatic Actuator Using On/Off Solenoid Valves," *IEEE/ASME Trans*., Vol. 2, No. 3, Sept.

Shen, Xiangrong, et al., 2004, "Nonlinear Averaging Applied to the Control of Pulse Width Modulated (PWM) Pneumatic System," Proc. of the 2004 *American Control Conf*.

Wang, Jihong et al., 1999, "A Practical Strategy for Servo Pneumatic Actuator Systems," Control Engineering Practice, Vol. 7, No. 7, pp. 1483～1488.

Wang, Xuesong et al., 2003, "Modeling and Control for Pneumatic Manipulator Based on Dynamic Neural Network," Proc. of *IEEE*, pp. 2231～2236.