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Closed-loop volume flow control algorithm for fast switching pneumatic valves with PWM signal

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ABSTRACT

In this paper, a closed-loop volume flow PWM control algorithm of fast switching pneumatic solenoid valves is studied on the basis of experimental results of fluid flow valve characteristics. Dynamic nonlinear behavior of fast switching valves is analyzed using state-of-the-art mass flow sensors. Minimal Pulse Width Modulation (PWM) pulse width and nonlinear flow characteristics depending on pulse width and pressure difference are observed. Based on experimental data, different approaches to mathematically describe correlation of volume flow, pressure difference and pulse width are given. Bilinear interpolation is found out to have the best correlation and is used to develop a closed-loop control algorithm. The algorithm was tested with controlling of Pneumatic Artificial Muscle (PAM) contraction/position with two fast switching valves and minimal PLC / microcontroller requirements were determined.

1. Introduction

Pneumatic actuators are mainly used in industry and are generally used for two position controls. Most of the time when the continuous position control is needed, pneumatic servo or proportional valves are used. Pneumatic servo valves are expensive and proportional valves do not have the fastest response time due to the spool deadband. The alternative is to use fast switching valves with digital control techniques with the goal to achieve linear flow control characteristics with the fastest possible response. The implementation of fast switching valves for position control using digital control techniques has been in development for the last 10 years (Messina, Giannoccaro, & Gentile, 2005; Najjari, Barakati, Mohammadi, Futohi, & Bostanian, 2014; Taghizadeh, Ghaffari, & Najafi, 2009a; Wang, Yang, Yang, Chen, & Guan, 2011). Main reasons for the use of the PWM control method for fast switching valves are reduction of valve response times, miniaturization of the valve control pistons and advanced electronics incorporated in this valves. Many researchers used PWM control techniques to drive pneumatic switching valves with good results. PWM signal frequencies used depend on the valve response time and are generally between 20–100 Hz (Taghizadeh et al., 2009a; Ahn & Nguyen, 2007; Belforte, Mauro, & Mattiazzo, 2004; Taghizadeh, Ghaffari, & Najafi, 2009b; Topçu, Yüksel, & Kamiş, 2006; Ying, Jia-fan, Can-jun, & Bin, 2007). Some efforts were made to develop electro-pneumatic valve models based on the electrical and pneumatic parts modeling and to use these models in a PWM driven pneumatic system (Ahn & Nguyen, 2007; Najjari et al., 2014; Ying et al., 2007). The relationship between the PWM pulse width and the fluid flow has always been defined to be linear, and only in one paper was the minimal PWM pulse used (Belforte et al., 2004) but at only one pressure difference. In the newest research, the relationship between the pressure difference and the coil current in pneumatic switching valves (Zhang, Lv, Yue, Li, & Yuan, 2014) is considered. There have also been attempts to use fuzzy logic and neural networks (Leephakpreeda, 2011) for PWM valve control. But no measurements or models have been made that directly describe the influence of the valve pressure difference on the PWM minimal pulse width. The standard equation of the fluid flow through a pneumatic valve is defined in the ISO 6358 standard (Eq. (1)) (ISO 6358-1, 2013), and is used in this form in almost all mathematical models of pneumatic switching valves.

$$\dot{V}_a = \begin{cases} P_1 C \dfrac{T_0}{T_1} \sqrt{1 - \left(\dfrac{\frac{P_2}{P_1} - b}{1 - b} \right)^2} & for\ \dfrac{P_2}{P_1} > b \\ P_1 C \dfrac{T_0}{T_1} & for\ \dfrac{p_2}{p_1} \le b. \end{cases} \tag{1}$$

Where $\dot{V}_a$ represents the volume flow (m^3/s), P_1 the absolute inlet pressure (Pa), P_2 the absolute outlet pressure (Pa), C the acoustic conductivity ($m^3/(s{*}P_a)$), T_0 the ambient temperature, T_1 the temperature

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of inlet air, and b the critical ratio. The data for the tested valve MHJ10-MF is: $C = 2.6167 \times 10^{-9}$ $\mathrm{m}^3/(\mathrm{s\ Pa})$ and $b = 0.433$ (FESTO, 2012). But this model does not describe what happens when the valve is controlled with the PWM signal and the valve is in constant transit states between being opened and closed. Therefore, this model can be used only when the valve is fully opened.

In this paper, we propose a new control algorithm for fast switching pneumatic valves which is based on the fluid flow characteristics measurements of the fast pneumatic switching valve MHJ10-MF. This valve has a response time of less than 1 ms (FESTO, 2012). The control algorithm includes the data about the response time which depends on the pressure difference, the optimal PWM control signal frequencies and the dependence of the flow characteristics on the PWM pulse width. The differential pressure and not pressure ratio as shown in Eq. (1) was used since the time needed for the valve to open changes depending on forces that push the valve control piston in closed position—these forces are directly connected to differential pressure. The algorithm delivers the fastest response possible and also allows fluid flow control with linear dependence on the control signal. It will be used in the future for the contraction control of pneumatic artificial muscles which have variable dynamic characteristics and need a very fast control loop. The similar algorithm with PWM control of valves was also developed for dosing pumps (Kramer, Petzold, & Weber, 2016).

If the desired accuracy and response is achieved, we will develop a new module with two fast switching valves for pneumatic muscle contraction control. This module will have two integrated fast switching valves and microcontroller with new control algorithm. With this control system we wish to achieve:

- Full contraction (40 mm) of pneumatic muscle DMS-20–200 in less than 0.5 s.
- The static position accuracy of less than ±0.1 mm.
- The algorithm must have the ability to be translated in to different programming/PLC languages.
- The control loop must be executed every 1 ms.
- Position sensor with minimum resolution of 0.03 mm and at least 250 Hz sampling rate (we used Li-Q25L with resolution 0.001 mm and linearity deviation <0.1% on full scale and sampling rate of 500 Hz).
- Pressure sensor with accuracy higher than 0.1 bar for range 0–6 bar (not needed if ΔP calculated). We used FESTO sensor SDET 22T (FESTO, 2008).

The minimum requirements for PLC/processor for controlling two fast switching valves are:

- 2x GPIO configurable to PWM output with PWM amplitude 3–30 V,
- 2x GPIO configured as analog input with at least 16 bit resolution and range 0–10 V (if similar position sensor is used).
- The minimum processor and RAM requirements will be defined at the end when the algorithm is developed and the performance of used controller CPU usage will be determined. The aim is that all IEC 61131–3 based PLC's will be compatible with this algorithm (Mazur, Chmiel, & Czerwinski, 2016).

2. Valve volume flow experimental data

The dependence of the fluid flow characteristics on the PWM pulse width and frequency was measured in previous work (Pipan & Herakovič, 2016). Experimental analysis was conducted at different input differential pressure values (ranging from $\Delta P = 0.1$ bar to $\Delta P = 6$ bar) and also at different PWM frequencies and pulse widths. The valve output pressure was always at ambiental pressure while the input pressure P_{IN} ranged from $P_{IN} = 0.1$ bar to $P_{IN} = 6$ bar of gauge pressure. The response time of 1 ms enabled us to use faster PWM

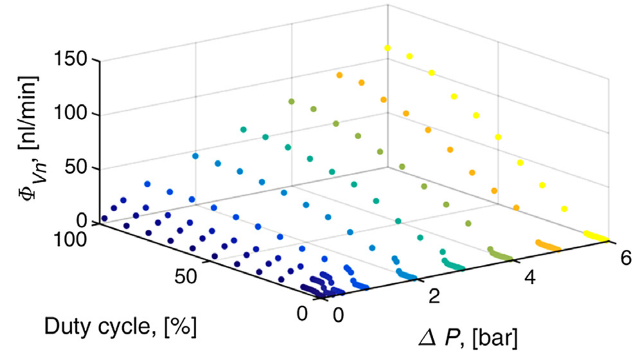

Fig. 1. Experimental analysis of pulse width (Duty Cycle—DC) and ΔP on volume flow at $f_{PWM} = 250$ Hz.

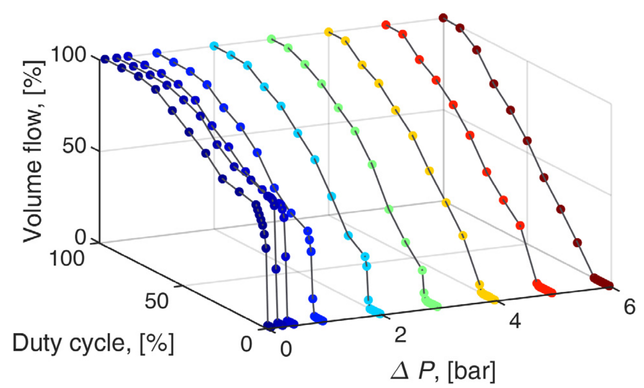

Fig. 2. Normalized volume flow data used for development of a closed-loop control algorithm.

frequencies. The analyzed frequencies are $f_{PWM} = 200$, 250 and 300 Hz. The most suitable frequency was determined to be $f_{PWM} = 250$ Hz. The test data used for valve characterization and development of a closed-loop control algorithm is presented in Fig. 1. The differential pressures presented in Fig. 1 are: $\Delta P = 0.1$ bar, 0.3 bar, 0.5 bar, 1 bar, 2 bar, 3 bar, 4 bar, 5 bar and 6 bar. These values were chosen based on our previous experimental results (Pipan & Herakovič, 2016) and accurately describe the nonlinear valve flow characteristics for ΔP =0.1–6 bar. With this experimental data we were able to determine how minimal pulse width (minimal duty cycle of PWM signal that is needed to start opening the valve) changes with change of differential pressures. In addition, the relation between different PWM duty cycles, volume flows and differential pressures was analyzed.

Our past experiment results (Pipan & Herakovič, 2016) show that differential pressures at different pressure levels ($\Delta P = 2$ bar for $P_{in} = 4$ and $P_{out} = 2$ bar or pressure level $P_{in} = 3$ bar and $P_{out} = 1$ bar) needs the same minimum pulse to open the valve to start opening. The normalized flow is also not affected.

All gathered data is provided as a set of Matlab data matrices for further analysis. The experimental data was then normalized to convert volume flow from [nl/min] to percentage, where 100% is maximum flow for a given ΔP. Fig. 2 presents normalized volume flow Φ [%] data. The relation between volume flow and pulse width is quasi linear for pressure differences ΔP >2 [bar].

However, at lower pressure differences, the initial response is steep and presents a problem for fitting mathematical equation as shown in detailed view in Fig. 3. The experimental data that describes the minimal pulse needed to open a fast switching valve at different pressures is shown in Fig. 4.