空気圧ロボットに応用する軽量・小型圧力制御弁の開発

○ジエン・スマディ、巽正之、平井慎一 (立命館大学)　本田顕真 (東レエンジニアリング (株))

Miniaturized Pneumatic Pressure Control Valve for Robotic Applications

*Sumadi JIEN, Masayuki TATSUMI, Shinichi HIRAI (Ritsumeikan University),
Kenshin HONDA (Toray Engineering Co., Ltd.)

Abstract— For pneumatic actuators to be applicable for robotics, the miniaturization of air compressors and control valves is indispensable. In connection to this, a new valve mechanism with unconstrained structure has been proposed for its potential of miniaturization. Our recent achievement of unconstrained valves, measuring $\phi 7 \times 9$ mm, has been much more compact than the conventional solenoid valves. This paper presents the investigation on the practicability of unconstrained valves for applications in robotics and discussion on the advantages and disadvantages of unconstrained valves. The discussed topic includes position control of pneumatic cylinders and pressure control for pneumatic rubber muscles.

Key Words: Unconstrained valve, Miniaturization, Pressure control

1. INTRODUCTION

Pneumatic actuators as one from many alternative actuations for robotics offer advantages of high power to weight ratios and compliance, compared to the widely used electric motors. Several pneumatic actuations in robotics include pneumatic artificial muscles (PAMs) [1], pneumatic motors [2, 3], and pneumatic cylinders [4]. Among these, PAMs are the most commonly used in robotics because it provides a much higher power to weight ratio than a conventional pneumatic cylinder [5], despite its drawback of low displacement. Pneumatic control can be summarized into two groups: (1) position control using servovalves or on-off valves, and (2) force control using pressure regulators or on-off valves. Servovalves and pressure regulators are expensive, and also their complex structures make it difficult for miniaturization. In contrast, pressure control using on-off valves is relatively inexpensive and has a higher frequency bandwidth than that using pressure regulators [6]. In regard to cost and total size, on-off valves are preferable.

The disadvantage of using pneumatic actuators is the hindrances caused by the weight and size of the bulky compressor and control valves. Therefore, miniaturization of valves is becoming a vital requirement for robotic use. Because the further miniaturization of conventional solenoid valves has many difficulties, a novel concept of miniaturized valves has been proposed using piezoelectric actuator with unconstrained structure to make the miniaturization easier [7]. Our current achievement of miniaturized valves, measuring $\phi 7 \times 9$ mm, has been reported in [8]. Fig. 1 shows a prototype of a miniaturized unconstrained valve in comparison to the solenoid valve and pilot-operated solenoid 3/2 directional control valve (DCV).

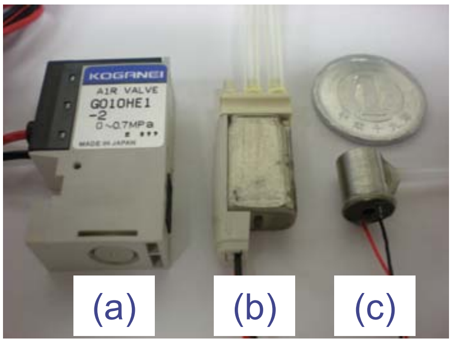


Fig.1 Comparison of pneumatic valves: (a) solenoid valve (dimensions $32 \times 26 \times 10$ mm), (b) pilot-operated solenoid 3/2 DCV (dimensions $32 \times 12 \times 7$ mm), and (c) prototype miniaturized unconstrained valve (dimensions $\phi 7 \times 9$ mm)

This paper mainly discusses the application issues of miniaturized unconstrained valves for robotics use, which covers the PWM-controlled pneumatic cylinders and miniaturization effort of pressure control valves for PAMs using on-off valves.

2. UNCONSTRAINED VALVES

Unconstrained valves lack of mechanical linkage between poppet and valve seat, therefore, high air pressure from the valve inlet is needed to automatically push the poppet into the valve seat. When the poppet will sit tight above the valve seat and if no voltage is exerted, the valve is at the close condition. For the valve to open, dynamic force is generated to realize an aperture between the poppet and valve seat as voltage is exerted on the piezoelectric actuator and a certain output flow rate is generated.

Control parameters that affect the flow behavior of an unconstrained valve are input voltage, input frequency and PWM switching. The valve input-output relationships: frequency-flow rate (f-Q), voltage-flow rate (V-Q), and PWM-flow rate (PWM-Q) behavior can be referred to [7].

3. POTENTIAL APPLICATIONS

Compared to solenoid valves that has only PWM-control mode supplied with a constant input voltage, unconstrained valves has several attractive features, i.e. small-size and variable-related flow rate regulation (f-Q, V-Q, and PWM-Q mode). However, a need of high pressure at the close condition is a disadvantage of unconstrained valves for practical use. In this section, the potential, advantages and disadvantages of unconstrained valves for use in pneumatic robots are discussed for two mostly known applications: PWM control of a single-acting pneumatic cylinders and pressure control of PAMs. Its advantages and disadvantages are also discussed.

3·1 PWM-controlled Valves for Pneumatic Cylinders

An unconstrained valve is able to do PWM switching control as has been verified in [7]. When the sum pressure difference between accumulator and cylinder is zero, there is no air pressure at work to constraint the poppet. In the position control of a single-acting pneumatic cylinder (Fig. 2), unconstrained valve is therefore impractical to be used at the supply side. However, the pressure difference at the exhaust side between cylinder and environment will always ensure a pressure drag to push the poppet to the valve seat, which enables the unconstrained valves to be used for control at exhaust side of the cylinder. Although hybridization of solenoid and unconstrained valves make the total size larger, it is still more compact compared to using the solenoid valves alone.

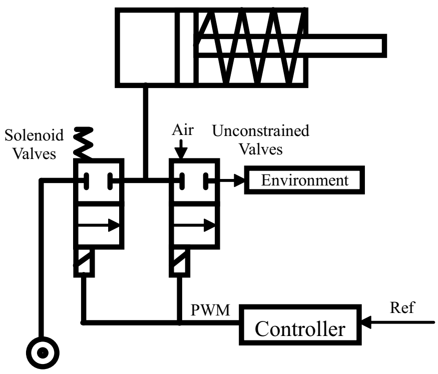
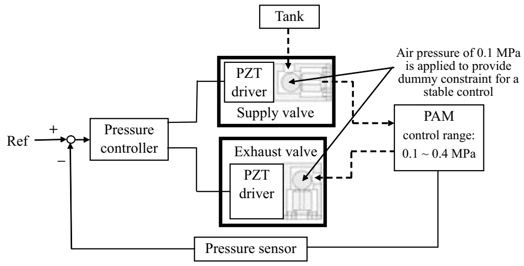


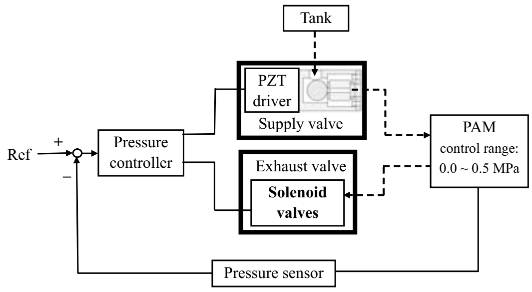
Fig.2 Unconstrained valves for control of a single-acting pneumatic cylinder

3·2 Pressure Control Valves

Unlike the position control scheme of pneumatic cylinders, the unconstrained valves are usable at both supply and exhaust sides for pressure control valve. However, two prerequisites have to be confined to prevent it ending in failure thatmay come from the valve's directional or positional changes, as shown in Fig. 3. The two combinations are: (a) with full unconstrained valves at both supply and exhaust sides (Fig. 3(a)), and (b) unconstrained valve at the supply line and solenoid valves at exhaust side (hybrid unconstrained - solenoid pressure control valve) in Fig. 3(b). There is always size and controllable range tradeoff associated with the combinations.



(a) Full unconstrained valves



(b) Hybrid unconstrained - solenoid valves

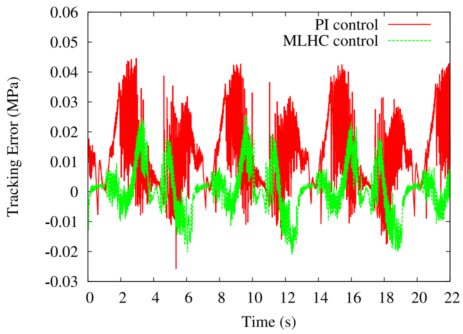
Fig.3 Implementation combinations of unconstrained valves for pressure control valves

4. MINIATURIZATION OF PRESSURE CONTROL VALVES

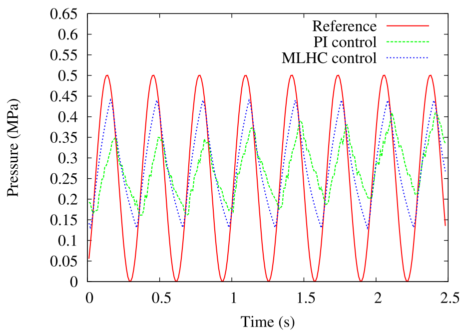
Comparisons in Fig. 1 reveal that an unconstrained valve is more promising for the development of a miniaturized pressure control valve, as the miniaturization of solenoid has been difficult. Since the unconstrained valves have been very different from the conventional constraint-type solenoid valves, this section aims to find the pressure control methodology for unconstrained valves based on solenoid valves know-how.

4·1 Using Solenoid on-off Valves

Pressure tracking control using solenoid on-off valves has been reported by R. Van Ham, et. al that hysteresis control is superior to the ordinary PWM controller [9]. To verify the obtained results, we compared two control algorithms: multi-level hysteresis control (MLHC) and PI control. Fig. 4 shows the tracking error and dynamic response results. As shown in Fig. 4(a) and (b), MLHC has smaller tracking error and higher dynamic response than PI control. Basically the overall results show an agreement with the statement in [9] that MLHC shows a better performance. As concerning the valve total size, MLHC algorithm will become larger in size because MLHC requires 4 valves whereas 2 valves are sufficient for PI control. It can be noticed that valve size and tracking accuracy has a tradeoff relationship for designing pressure control valves.



(a) Tracking error



(b) Dynamic response

Fig.4 Experimental results of PI and MLHC control for solenoid valves. (a) Pressure tracking error for sinusoidal input at 100 mHz, (b) Dynamic response for sinusoidal input at 2 Hz

4·2 Using Unconstrained Valves

Experimental evaluation of pressure control algorithms and assessment on control performance for unconstrained valves has been summarized in [10], comparing four control algorithms: (a) hysteresis control, (b) multi-level hysteresis control (MLHC), (c) proportional PWM control, and (d) multimode switching control. Comparisons showed that MLHC provided the best tracking control algorithm, which is similar to the results of solenoid valves.

Because of the inherent frequency-adjustable flow rate (f - Q mode), multi-level hysteresis control using unconstrained valves requires only two valves, whereas solenoid valves require about four to six valves. The end result indicated that unconstrained valves are not only potential for miniaturization but also is crucial for the design of a miniaturized pressure control valve.

4·3 Comparison

To assess the tracking performance, different pressure control devices built of solenoid and unconstrained valves were tested for tracking a reference 50 mHz sinusoidal input waveform and the result is given in Fig. 5. The result of pressure regulatoris also added for comparison purposes of valve performance and total size. Fig. 6 shows the size comparison between the newly developed unconstrained pressure control valve and other pressure control devices, indicating that unconstrained pressure control valve is much more compact.

A reference of similar research to the miniaturization effort of pressure control valve is in [1]. In the beginning of actuator control, pneumatic control control has not been able to surpass the accuracy of electric motors. The tracking inaccuracy of pneumatic actuators can be improved by an alternative hybrid pneumatic/electric actuation [1, 3]. For this reason, the inaccurate tracking performance of unconstrained pressure control valves is considered acceptable.

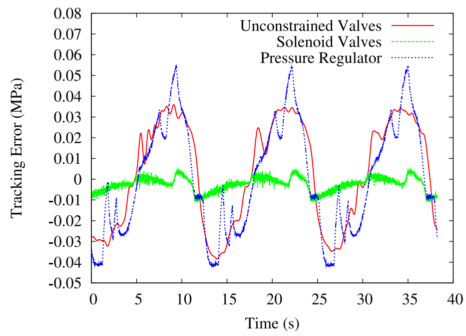


Fig.5 Comparison of pressure tracking error at 50 mHz

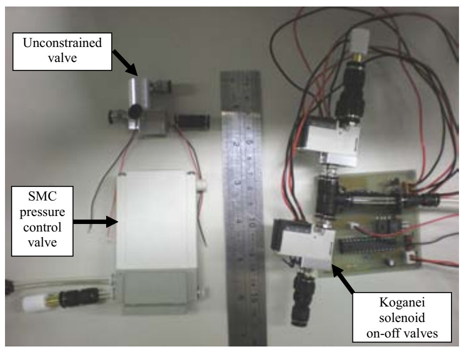


Fig.6 Unconstrained valves having the smallest size among the pressure control devices

5. PNEUMATIC SERVODRIVE

A newly developed small-sized pneumatic servodrive is composed of a miniaturized unconstrained pressure control valve and a mini homemade artificial muscle (Fig. 7). The mini PAM was made of FESTO rubber tube $\phi 3 \times 30$ mm. Fig. 8 shows the experimental results of pressure tracking performance and dynamic response of the servodrive. The frequency bandwidth is 0.3 Hz, as indicated by the bode diagram in Fig. 8(b).

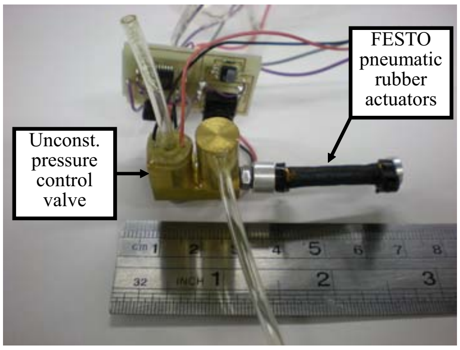
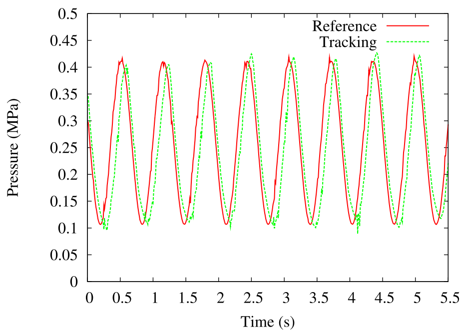
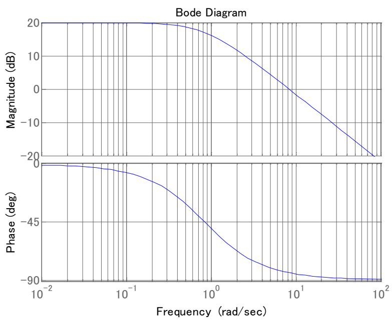


Fig.7 Miniaturized pneumatic servodrive



(a) Tracking performance at 1 Hz



(b) Dynamic response

Fig.8 Pressure tracking performance of a mini servodrive driven by unconstrained valves

6. CONCLUSION

This paper describes the potential applications of unconstrained valves for position control and pressure control valves. Experimental results show a similar result for both solenoid and unconstrained valves that multi-level hysteresis control has the best tracking performance. Comparisons indicated that unconstrained valves are suitable for pressure control of PAMs and have a high potential for further miniaturization. Although the unconstrained mechanism imposes a restriction on the control implementation of pneumatic actuators, hybrid combination of solenoid and unconstrained valves can be an alternative solution. Selection has to be made according to the controllable range, size, and tracking accuracy requirements.

7. FUTURE WORK

Future work includes the further miniaturization of unconstrained valves as well as real implementation of unconstrained pressure control valves for pneumatic robots.

[1] D. Shin, I. Sardellitti and O. Khatib: "A Hybrid Actuation Approach for Human-Friendly Robot Design", 2008 IEEE Int. Conf. on Robotics and Automation, pp.1747-1752, USA, 2008.

[2] K. Uzuka, I. Enomoto and K. Suzumori: "Comparative Assessment of Several Nutation Motor Types", IEEE/ASME Transactions on Mechatronics, pp.82-92, 2009.

[3] F. Takemura, et. al: "Control of a Hybrid Pneumatic/Electric Motor", Proc. of the 2000 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp.209-214, 2000.

[4] J. H. Cocatre-Zilgien, F. Delcomyn and J. M. Hart: "Performance of a Muscle-like "Leaky" Pneumatic Actuator Powered by Modulated Air Pulses", Journal of Robotic Systems 13(6), pp.379-390, 1990.

[5] B. Tondu and P. Lopez: "The McKibben muscle and its use in actuating robot-arms showing similarities with human arm behavior", The Industrial Robot, Bedford, Vol. 24, 1997.

[6] Y. Chen, et. al: "Design and Hybrid Control of the Pneumatic Force-Feedback Systems for Arm-Exoskeleton by Using On-Off Valve", Mechatronics 17, pp.325-335, 2007.

[7] S. Jien, Y. Ogawa, S. Hirai and K. Honda: "Performance Evaluation of a Miniaturized Unconstrained Digital On-Off Switching Valve", 2008 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics, China, 2008.

[8] M. Tatsumi, M. Ito, S. Jien, S. Hirai and K. Honda: "Influence of Shape and Material to Miniaturize Unconstrained Vibration Pneumatic Poppet Valves", The Proc. on Spring Conf. of Japan Fluid Power System Society 2009, pp.125-127, Japan, 2009.

[9] R. Van Ham, B. Verrelst, F. Daerden and D. Lefeber: "Pressure Control with On-Off Valves of Pleated Pneumatic Artificial Muscles in a Modular One-Dimensional Rotational Joint", Int. Conf. on Humanoid Robots, 2003.

[10] S. Jien, S. Hirai, Y. Ogawa, M. Ito and K. Honda: "Pressure Control Valve for McKibben Artificial Muscle Actuators with Miniaturized Pneumatic On/Off Valves", 2009 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics, Singapore, 2009.