Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Control Engineering Practice 15 (2007) 1161–1168
CONTROL ENGINEERING PRACTICE
www.elsevier.com/locate/conengprac

Modeling and self-tuning pressure regulator design for pneumatic-pressure–load systems

Xue-Song Wang[a,*], Yu-Hu Cheng[a], Guang-Zheng Peng[b]

[a]*School of Information and Electrical Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221008, China*
[b]*School of Information Science and Technology, Beijing Institute of Technology, Beijing 100081, China*

Received 15 September 2005; accepted 9 February 2007
Available online 27 March 2007

Abstract

This paper presents a dynamic model and a design method for an accurate self-tuning pressure regulator for pneumatic-pressure–load systems that have some special characteristics such as being nonlinear and time-varying. A mathematical model is derived, which consists of a chamber continuity equation, an orifice flow equation and a force balance equation of the spool. Based on a theoretical analysis of the system dynamics, a three-order controlled auto-regressive moving average (CARMA) model is used to describe the practical pressure–load systems. Then a linear quadratic Gaussian self-tuning pressure regulator is designed to realize an adaptive control of pressure in the chamber. Because the system parameters are time-varying and the system states are difficult to detect, the recursive forgetting factor least-squares algorithm and the Kalman filtering method are adopted to estimate the system parameters and the system states. Experimental results show that the proposed self-tuning pressure regulator can be adapted to parameters which vary with such factors as the volume of the chamber and the setting pressure and that better dynamic and static performances can be obtained.

Keywords: Pneumatic-pressure–load systems; Electro-pneumatic proportional pressure valve; Modeling; Self-tuning regulator; Linear quadratic Gaussian

1. Introduction

Since pneumatically driven systems have many distinct characteristics of energy-saving, cleanliness, simple structure and operation, high efficiency and are suitable for working in a harsh environment, they have been extensively used for many years in robot driven systems and industrial automation (Pu, Moore, & Wong, 2000). Recently, the appearance and development of electro-pneumatic proportional components place pneumatic control techniques beyond the restrictions of point-to-point control. Electro-pneumatic proportional control components can convert an analog electrical input signal into an outlet flow (i.e., an electro-pneumatic proportional flow valve) or a pressure (i.e., an electro-pneumatic proportional pressure valve). Therefore, they can dramatically simplify pneumatic and electric circuits. As well, they provide the necessary parts for pneumatic servo-feedback control systems such as position (Lee, Choi, & Choi, 2002; Smaoui, Brun, & Thomasset, 2006), speed (Renn & Liao, 2004), pressure (Pandian, Takemura, Hayakawa, & Kawamura, 2002) and force (Khayati, Bigras, & Dessaint, 2004).

In the past few years a considerable amount of interest has been shown in pneumatic position servo-systems. From the point of view of controller designs, several methods have been investigated and developed to improve the position control performance of pneumatic actuator systems. One of the ideas that has been used to control pneumatic position servo-systems is the state-space linearization method (Xiang & Wikander, 2004). Unfortunately, this approach is not very efficient for a large operational range because pneumatic systems are highly nonlinear. Wang, Pu, and Moore (1999) proposed a modified proportional, integral and derivative (PID) control strategy for servo-pneumatic actuator systems, but the acceleration feedback signal required in this control strategy was difficult to obtain in practice. A study of a gain-scheduling method for controlling the motion of pneumatic actuators

---

*Corresponding author. Tel./fax: +86 516 83883204.
E-mail address: wangxuesongcumt@163.com (X.-S. Wang).

0967-0661/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conengprac.2007.02.001

was published by Pu, Moore, Harrison, and Weston (1993). This scheduling scheme was based on a simplified plant model without the use of any prior knowledge, such as the dynamic behavior of the pressure build-up in the actuator chambers. Likewise, the global stability of the closed-loop system was not shown. For this reason, Schultea and Hahn (2004) designed a fuzzy state feedback gain-scheduling controller for servo-pneumatic actuators. Their proposed scheme utilized prior physical knowledge to define the Takagi–Sugeno model structure such as the number of local models, the order of the linear model and the scheduling vector. A control law was formulated as an interpolation of local linear state-space controllers, each designed by a pole placement using linear state-space models. As stated above, this linearization method is not very efficient for a large operational range because pneumatic systems are highly nonlinear. To be efficient at a larger operational range, an adaptive controller has been applied to pneumatic systems which considers nonlinear terms as linear time-varying ones (Sakamoto, Matsushita, Mizukami, & Tanaka, 2002). This approach is efficient only when the linear parameters vary slowly with time. An alternative way to handle the nonlinearity is to design controllers without explicitly using the mathematical model of the plant. Fuzzy control (Gao & Feng, 2005; Xue, Peng, Fan, & Wu, 2004) and neural network control (Wang & Peng, 2003) are typical examples of this alternative approach. In fuzzy control, the nonlinearity is taken into account as fuzzy rules. In neural network control, they are compensated for by neural network learning.

Among various pneumatic actuator systems, pneumatic-pressure–load systems constructed by electro-pneumatic proportional pressure valves are very important intensity testing devices used in many types of equipment such as aircraft and tail props in a wind tunnel. Moreover, they have been extensively used in the fields of robots, metallurgy and various industrial processing systems. Although the pneumatic-pressure–load technique has received wide applications, research in the design of accurate pressure controllers at present is quite limited in comparison with that of position servo-controls. The research activity, such as it is, can be categorized into two types. First, in order to improve the control performance of pneumatic position servo-systems, pressure control was introduced as an inner control loop, while the position feedback was viewed as an outer control loop. Noritsugu and Takaiwa (1995) carried out a robust control of a pneumatic position servo-system with a pulse code modulate (PCM) digital control valve, using a linearization pressure control inner loop. A disturbance observer was employed to improve the pressure response and compensate the effect of friction force and parametric variation. Consequently, improvements in robustness against payload and in positioning accuracy had been attained. Lee et al. (2002) investigated a position control for a double-acting, rodless cylinder. Their proposed controller had an inner linearization pressure control loop and an outer position control loop. A PID controller with feedback linearization was used in the pressure control loop to nullify the nonlinearity arising from the compressibility of air. The position controller was also a PID controller augmented with friction compensation using either a neural network or a nonlinear observer. But such linearization controllers only work well within a certain operating region and their performance and behavior outside the range are unknown. Second, as an independent control approach, the most commonly used pressure control method is the open-loop control, given the characteristic working curve between the input voltage and the output pressure of a proportional valve, for example, the control method by Sorli, Figliolini, and Pastorelli (2004). But the control accuracy is severely affected by its nonlinear characteristics. Robust control approaches to model tracking have been a very active area of research. Pandian et al. (2002) presented a sliding-mode pressure observer/controller for pneumatic cylinder actuators. The feedback gains were made high, so that the resulting chattering of input noise would cause a fluctuation in pressure. Also, the observer could not reproduce this fluctuation. Then, the observer-based tracking response had a slight oscillation and resulted in a noticeable steady-state error arising from the actuator and high-frequency chattering. Therefore, this kind of robust control method is not practical.

In fact, pneumatic-pressure–load systems are difficult to control accurately because of the nonlinearity associated with air compressibility, the time delay due to the slow propagation of the air pressure waves and the large associated friction forces. In addition, the parametric variation due to leakage and the unpredictable environment of industrial situations will further complicate the problem. It is known that a distinct advantage of the controller, based on a linear quadratic Gaussian (LQG) method, is that a satisfactory control performance can be obtained merely under the condition that the weighted matrices of the state and the control variables are determined according to the system response curve. In this way, the complex computation of the closed-loop poles based on a performance index can be omitted. Therefore, a LQG self-tuning pressure regulator for pneumatic-pressure–load systems is proposed in our paper. The parameters and the states of pressure servo-systems are identified on-line by observing the input–output data. Based on the identified system model, control voltage can be determined according to a quadratic performance index so that an adaptive control for pneumatic-pressure–load systems can be realized.

The paper is organized as follows. The experimental setup and the dynamic model of a pneumatic-pressure–load system are given in Section 2. In Section 3, the idea and the algorithm steps of designing a self-tuning pressure regulator are described. In order to verify the validity of the proposed control method, some experimental results are presented and analyzed in Section 4. Finally, conclusions are drawn in Section 5.