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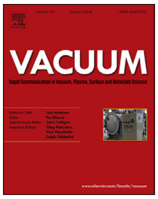

# Adaptive robust control of dynamic gas pressure in a vacuum servo system

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ABSTRACT

This paper presents a system based on servo technology for controlling the dynamic gas pressure in a vacuum system. The electro-pneumatic proportional directional valve (EPPDV) is used as a control regulator, which places vacuum control techniques beyond the restrictions of point-to-point control. The two major components of the system, the chamber and the EPPDV are analyzed to derive a system mathematical model. Due to the air compression, valve leakage, there exist parametric uncertainties and uncertain nonlinearities in the vacuum system. An adaptive robust nonlinear controller is proposed to deal with these uncertainties effectively. The proposed controller employs on-line update of the uncertain parameters to improve the precision and utilizes the sliding mode control method to attenuate the effects of uncertain nonlinearities. In order to solve the conflicts between the sliding mode control design and the adaptive control design, the projection mapping is used so that the parameter estimates are kept within a certain range. The experimental results show that using EPPV as the regulator in a vacuum servo system is feasible, and the proposed controller is effective in dealing with the nonlinearity.

## 1. Introduction

The vacuum pressure control system has been studied extensively by many scholars [1–5], and some findings were widely applied in industrial fields, such as the simulation of dynamic atmospheric environments, calibration of meteorological instruments and research of humidity generation technologies. The vacuum valves are important parts of vacuum systems, which are usually used as cut-off component or gas flow regulator. In Ref. [1], a needle valve derived by a small servo motor, a kind of flow regulating valve, was used to control gas throughput so as to maintain a constant pressure within a vacuum chamber. Dong [5] adopted parallel structures combining rough with fine regulating valves to adjust the vacuum pressures of the double-level dynamic vacuum system. However, these researchers only realized point-to-point pressure control. Studies on vacuum servo systems have scarcely been seen because of the lack of vacuum proportional/servo control components.

For implementing continuous control of vacuum pressure, pneumatic servo technology is introduced. Li [6] presented a pressure and vacuum continuous control system, which consists of a hybrid pump, a chamber and an electro-pneumatic proportional directional valve (EPPDV). By altering input signal of the EPPDV, the chamber vacuum pressure can be real-time controlled when tracking sinusoidal and square wave. The EPPDV is the key element in the pneumatic servo system. There are two types of electro-pneumatic proportional valves (EPPV), the EPPDV and the electro-pneumatic proportional pressure valve (EPPPV). EPPDV can convert an analogue electrical input signal into an outlet flow, and another kind of proportional valve, EPPPV, can converts an input electrical signal into a specified outlet pressure. Thus, EPPVs provide the necessary parts for pneumatic servo systems such as position [8,9], speed [10], pressure [11] and force [12]. Normally, EPPDV can provide better dynamic response than EPPPV. At present, the one of the best EPPDVs has a dynamic response of 115 Hz and a spool position accuracy of 0.4% to the full stroke [7]. The bandwidth of the EPPPV introduce in Ref. [20] is not more than 5 Hz. EPPPV is mostly used for constant pressure control [13,14]. Lu [13] presented a constant pressure control system that consists of frictionless cylinders, a large tank and an EPPPV. A hybrid controller combined with Bang-Bang, PD controller and fuzzy PID was proposed to minimize the pressure fluctuations in cylinders. In

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Ref. [14], the pneumatic-pressure-load system was constructed by the chamber, EPPPV and pressure sensor, and applied to intensity testing devices. In the pneumatic pressure signal generator [15], EPPDV was used to control the air-flow rates into and out of the chamber to track sine pressure signal.

EPPDV adopts the spool design and clearance seal to obtain low friction forces and improves dynamic response. With such structure, the valve leakage is inevitable. In Ref. [6], the minimum controlled pressure is 20 kPa, and the effect of valve leakage was not considered. In this paper, we discuss the lower pressure control in a vacuum servo system. The principle sketch of the vacuum pressure servo system is shown in Fig. 1. Chamber pressure $p$ and vacuum pump inlet pressure $p_v$ are measured by pressure sensors. The computer gets the pressure signal and outputs a control command to EPPDV, which controls the airflow rate and the process of chamber charging and discharging. The vacuum servo system can be applied in the hardware-in-the-loop simulation for aerospace engineering, which produces a continuous pressure signal according to the flight altitude command to simulate the atmospheric environment variation during the flight. With the rapid development of aircraft, the flight altitude is progressively increasing. Therefore, the continually enlarged pressure range of the vacuum servo system is demanded. Thus, the system would be subjected to a considerable amount of the valve leakage.

For the vacuum servo system shown in Fig. 1, there exist rather severe parametric uncertainties and uncertain nonlinearities, which are caused by the valve leakage, spool dynamic and modeling errors. For the constant pressure control or step response of pressure control in vacuum systems, only PID algorithm is needed to achieve better steady-state error. However, for the tracking control of sinusoidal and even arbitrary pressure dependence as a function of time, it is difficult to realize the high-precision gas pressure tracking for PID controller. The adaptive robust control (ARC), which has been widely applied to the nonlinear systems [16–19], such as precision motion control of linear motors [16], posture control of a parallel manipulator [17], and output force tracking control of pneumatic cylinder [18]. ARC has the advantages to deal with the parametric uncertainties and uncertain nonlinearities. In Ref. [16], a discontinuous projection based ARC controller is constructed to achieve precision motion control of linear motors with negligible electrical. In the servo-pneumatic system with the pneumatic cylinder [18], ARC controller was adopted to achieve high-accuracy output force trajectory tracking for the system. In this paper, the adaptive robust control strategy is applied to reduce the uncertain nonlinearities and parametric uncertainties. For the vacuum servo system with EPPDV, the work that designing adaptive robust controller is to achieve pressure control with lower pressure and higher frequency to satisfy the requirements of aircraft hardware-in-the-loop simulation. The minimum controlled pressure reaches 2 kPa, and the frequency and amplitude of tracing sinusoidal curve are 2 Hz and 0.4 kPa respectively in this study.

## 2. Modeling of the vacuum servo system

The schematic diagram of the vacuum servo system is shown in Fig. 2. The system consists of the vacuum pump, 5/3-way EPPDV, constant volume chamber, high-precision pressure sensors and computer. As shown in Fig. 2, the 5/3-way EPPDV is three positions proportional valve with 5 ports. There are three ports connected with atmosphere, vacuum pump and chamber respectively. Other ports are blocked. The working process is composed of charging mode and discharging mode. In the charging mode, the chamber is connected to the atmosphere through the EPPDV. Due to the pressure difference between the atmosphere and the chamber, air flows into the chamber to increase pressure. While in the discharging mode, the air in the chamber is released by a vacuum pump through the valve and the pressure will decrease. In both work modes, the airflow rate can be regulated by the EPPDV.

### 2.1. Proportional valve

The model of the proportional valve can be divided into a mechanical part that is responsible for the movement of the spool and a pneumatic part that describes the flow through the valve as a function of the valve's input signal or spool position. In this study, the bandwidth of the EPPDV (FESTO, MPYE-5-1/8-HF-010-B) is about 95 Hz, which is much higher than the bandwidth of the vacuum servo system, thus the dynamics of the mechanical part of the valve can be neglected.

The airflow through one orifice of the proportional valve can be considered as one-dimensional compressible flow in a nozzle. Depending on the downstream pressure $p_d$ and the upstream pressure $p_u$ of the orifice, the status of the flow can be classified as choked flow and under-chocked flow. Reference [21] presents a thorough discussion of the models of the mass flow rate through a pneumatic component and shows the most detailed description of a restriction is given by the ISO model.

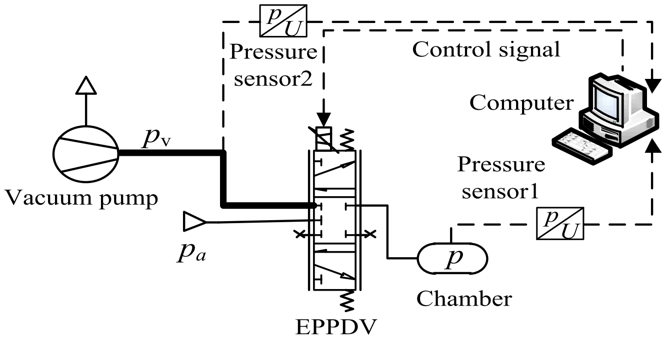

**Fig. 2.** Schematic diagram of vacuum servo system.

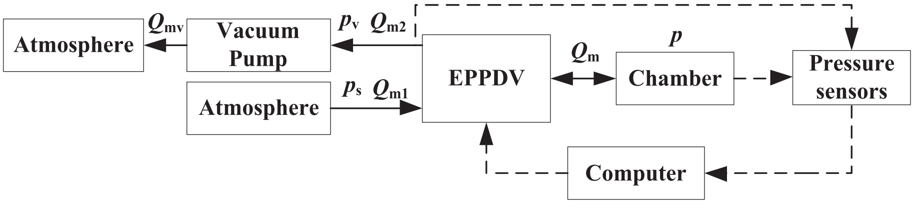

**Fig. 1.** Principle sketch of vacuum servo system.