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Observer-based adaptive sliding mode control for pneumatic servo system

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ABSTRACT

In this paper, an extended state observer (ESO) being incorporated with the adaptive sliding mode control theory is proposed to deal with a nonlinear pneumatic servo system characterized with input dead-zone, unknown system function, and external disturbance. The ESO is used to estimate system state variables of the unknown nonlinear system; the adaptive law is employed to compensate for dead-zone system behavior. Positioning experiments based on the derived control strategy were performed. As one example of positioning results, the positioning accuracy with sub-micrometers range was verified for both forward and backward actuations with step commands of 3 mm. The control scheme provided in this paper that can significantly improve the positioning performance of a traditional pneumatic servo system is demonstrated.

1. Introduction

In recent year, pneumatic servo system has been widely used in automation industry with low cost, fast speed, long stroke. However, due to the drawbacks of compressibility of air, nonlinear friction force existing on contact surfaces, and nonlinear dead-zone characteristic of servo valve, the pneumatic positioning system usually cannot achieve high precision positioning accuracy. In order to improve the positioning performance of pneumatic servo systems, many methods have been proposed, such as sliding mode [1–3], neural network [4], fuzzy PWM [5], and the scheme of the pneumatic system combined with piezoelectric actuators [6–8]. In addition, they also have been reported as effectiveness to compensate for the stick-slip phenomenon by adding a velocity compensation signal to the servo valve [9] and by using a piezoelectric dither [10].

Although the sliding mode control scheme with excellent robustness has been widely applied to pneumatic servo systems, it requires that the derivative of output variable of the control system must be determined. This brings about the difficulty in controller design. Therefore, in this paper, an extended state observer (ESO) [11] is proposed to estimate the immeasurable system state variables and system uncertainties of a pneumatic servo positioning system, and then referring to the adaptive sliding mode control [12] to derive an observer-based adaptive sliding control scheme through a so-called almost sliding surface. It is validated that the proposed control scheme can significantly improve positioning performance in a pneumatic servo system.

2. Pneumatic servo system

The pneumatic servo system is schematically shown in Fig. 1 and the photograph of experimental equipment is shown in Fig. 2. The pneumatic cylinder (Airpel, ø10 × 12 mm) is fixed to the base. The target object of sliding table with a dimension of 35 mm × 25 mm × 35 mm rests on the V-grooved base. The pneumatic cylinder is controlled by a proportional valve (Festo, MPYE-5-M5-010B). A 12-bit digital-to-analog (D/A) converter is used to transfer the control command to the proportional valve (PV) via a power amplifier (Amp). A non-contact type linear encoder (Renishaw, RGH25F2000) with the resolution of 10 nm is mounted beside the sliding table and the displacement of sliding table is measured by the linear encoder through digital input/output (DIO) ports. To avoid environmental disturbance, the experimental setup is set on the anti-vibration air table.

In order to analyze the dynamic model of pneumatic servo system, a schematic drawing of pneumatic servo system is depicted in Fig. 3. Although the heat of the atmosphere might give a great influence on the servo system, for simplicity, the variation of temperature is regarded as a disturbance and the pneumatic system is assumed as isothermal. Therefore, the pneumatic system is

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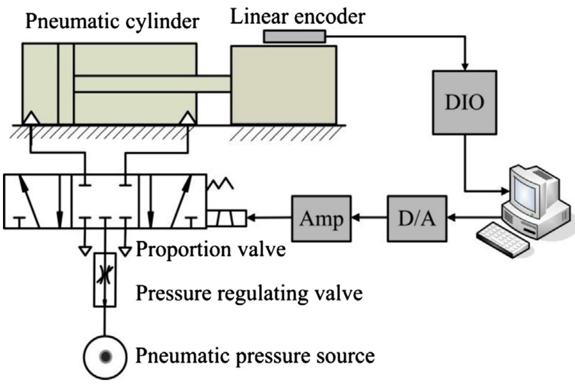

Fig. 1. Pneumatic servo system.

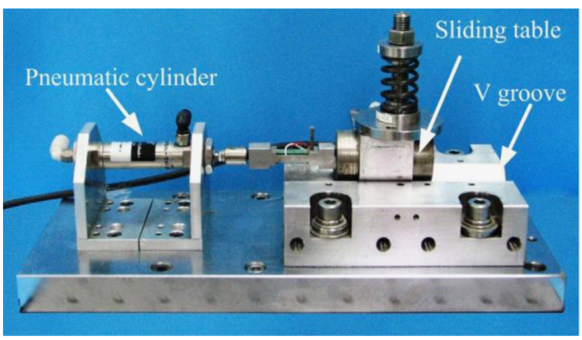

Fig. 2. Photograph of the experimental equipment.

isothermal, the thermo-dynamic equation of the left chamber in Fig. 3 can be written as

$$P_a V_a = m_a R T \tag{1}$$

where
P_a: pressure in left chamber
V_a: volume of left chamber
m_a: flow rate in left chamber
R: gas constant
T: temperature of the air

On differentiation of the Eq. (1) and arranging, the flow rate in left chamber is as follows,

$$\dot{m}_a = \frac{1}{RT}(\dot{P}_a A_a y + P_a A_a \dot{y}) \tag{2}$$

where y is the piston displacement measured from left end wall and A_a is the piston cross-sectional area. Similarly, the flow rate in the right chamber can be written as

$$\dot{m}_b = \frac{1}{RT}[\dot{P}_b A_b (L - y) - P_b A_b \dot{y}] \tag{3}$$

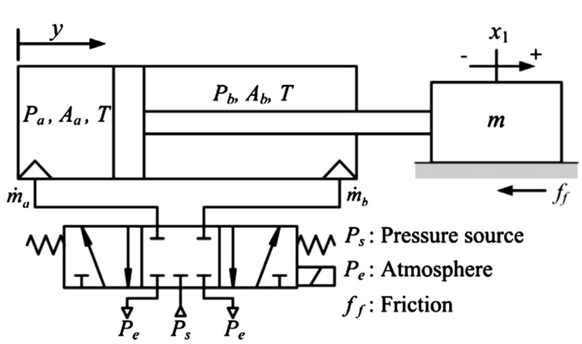

Fig. 3. Schematic of pneumatic servo system.

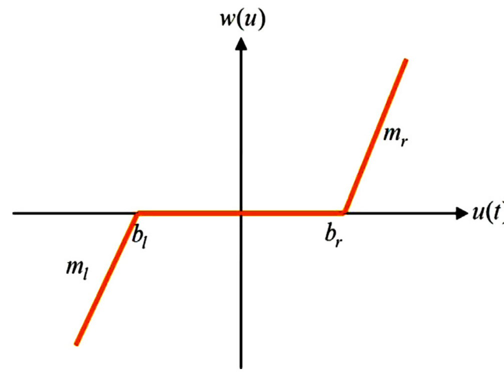

Fig. 4. Dead-zone function.

where L is the stroke of cylinder, and P_b and V_b are pressure and effective volume in the right chamber, respectively.

Considering Eqs. (2) and (3), if the flow rates are taken into account in implementing a servo system, the pressures in both the cylinder chambers should be measured. This will bring the control loop complicated. For simplicity, the pneumatic system is regarded as a second-order system by employing a reduced order sliding mode control scheme [1]. According to the pneumatic servo system with reduced order, the dynamic equation can be represented as

$$m\frac{d^2x_1}{dt^2} + \eta\frac{dx_1}{dt} = P_a A_a - P_b A_b = F_{\text{applied}} \tag{4}$$

where
m: mass of sliding table
η: damping coefficient
F_{applied}: net force of pneumatic cylinder
$x_1(t)$: displacement of sliding table

Although Eq. (4) is explicitly a second-order linear differential equation, actually, nonlinear characteristics exist in compressibility of air, friction force, and proportional valve. Therefore, considering the pneumatic servos system with nonlinear characteristics, Eq. (4) can be rewritten as follows [2],

$$\frac{d^2x_1}{dt^2} = \frac{-f_f(\dot{x}_1) - f_P(x_1, \dot{x}_1)}{m} + d(t) + \frac{F_{\text{applied}}}{m} \tag{5}$$

$f_f(\dot{x}_1)$: nonlinear function of friction
$f_P(x_1, \dot{x}_1)$: nonlinear function of air compressibility
$d(t)$: external disturbance and system unmodeled error

In Eq. (5), the friction and air compressibility are unknown nonlinear functions; the pneumatic servo system is a kind of nonlinear input dead-zone system caused by the proportional valve and nonlinear friction. In this paper, to cope well with the pneumatic servo system, an ESO is employed to estimate unknown nonlinear function and disturbance of system. The nonlinear differential equation having dead-zone characteristic of Eq. (5) can be rewritten as follows,

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(X, t) + d(t) + B(t)w(u) = a(t) \end{cases} \tag{6}$$

where
$X(t) = [x_1(t) x_2(t)]^T \in R^2$ is a system state vector, $f(X, t) \in R$ is an unknown nonlinear function of the system, $B(t) \in R$ is an unknown control gain, $u(t) \in R$ is control input, and $d(t) \in R$ is a disturbance.