AN EFICIENT CONTROL ALGORITHM FOR CONTROLLING A PNEUMATIC SYSTEM

MỘT THUẬT TOÁN HIỆU QUẢ ĐỂ ĐIỀU KHIỂN HỆ THỐNG KHÍ NÉN

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ABSTRACT

Position control of pneumatic systems is a challenging task because of their nonlinear properties and difficulties in acquiring system parameters. Designing a suitable controller in such situation is very important. The designed control scheme must operate properly to deal with the nonlinear characteristics and lack of system parameter information.

Variable structure based sliding mode control (SMC) is proposed as a control algorithm that matches with nonlinear systems because of its robustness and insensitivity to system uncertainties. However, due to nonzero tracking error inside boundary layer, SMC should be combined with another control action to gain good performances.

In this paper, a flexible controller which is a combination between SMC and PID controller called multimode PID-SMC is addressed to pneumatic system control problem. This proposed control scheme extracts advantages of both SMC and PID controller. The control quality of multimode SMC-PID is acceptable in some specific cases where the required accuracy is not so high.

TÓM TẮT

Hệ thống điều khiển vị trí của xi lanh khí nén cần phải được thiết kế sao cho xử lý có hiệu quả với tính phi tuyến và trường hợp thiếu thông tin về tham số của hệ thống.

Một sơ đồ điều khiển trượt (SMC) có cấu trúc thay đổi được đề nghị do tính bền vững của nó và tính không nhạy với những bất định của đối tượng. Tuy nhiên do SMC không thỏa mãn điều khiển vô sai trong lớp biên nên cần phối hợp với tác động điều khiển khác, trong trường hợp này là điều khiển PID. Hệ như vậy gọi là bộ điều khiển PID-SMC đa chế độ.

Các kết quả mô phỏng và thực nghiệm đã chỉ ra hệ thống điều khiển đã khai thác được thế mạnh của cả SMC và PID.

I. BACKGROUND

Pneumatic control systems have played an important role in industrial application due to their high efficiency and reliability, high power to weight ratio.

In comparison with electrical machines, pneumatic systems provide a slower output response and if compare to hydraulic system, pneumatic systems can not be more powerful. However, pneumatic systems are so popular in a wide range of application. Pneumatic systems have a high reliability thank to their fewer moving part, compactness, torque and varied speed in an extensive application range. The saturation and loses in pneumatic components are at a lower level than that in electrical machines, and in addition, can operate under continuous, intermittent, reversing and stalled conditions without damages. In term of energy storage, it is simple to use pneumatic lines and accumulators, unlike hydraulic systems, no return lines are required.

In many applications of pneumatic systems, when linear motion is required, piston control always is the first choice. In this simple application that only required the piston produces back and forth motions between the two endpoints, control valves that control piston simply operate in on/off mode. With the development of advanced technology, a combination between pneumatic actuators and electronic devices was established to take full advantages of them (high power of pneumatic actuators and efficient calculation ability of electronic devices). This combination is called electro-pneumatic devices and provides an ability that allows the piston to reach any predefined points in its itinerary.

However, it is recorded that pneumatic part in electro-pneumatic devices has a strongly nonlinear behavior [1,2]. Nonlinearity in flow/pressure characteristics, variation in trapped air volume due to piston motion, and air compressibility are major source of nonlinearity in pneumatic systems. These system behaviors make a position controller design a difficult task.

II. MODEL FORMULATION

2.1 Pneumatic mathematical model

In state space, define state space variable vector **x** as $x = \left[\Delta P_1, \Delta P_2, \Delta x, \Delta \dot{x}\right]^T$, the state space form of a pneumatic control system is described below [3]

$$\begin{cases} \dot{\mathbf{x}} = \begin{bmatrix} 0 & 0 & 0 & -\frac{\gamma A P_{10}}{V_{10}} \\ 0 & 0 & 0 & \frac{\gamma A P_{20}}{V_{20}} \\ 0 & 0 & 0 & 1 \\ \frac{A}{M} & -\frac{A}{M} & -\frac{k}{M} & -\frac{C}{M} \end{bmatrix} \mathbf{x} + \begin{bmatrix} K\frac{\gamma RT}{V_{10}} \\ -K\frac{\gamma RT}{V_{20}} \\ 0 \\ 0 \end{bmatrix} \Delta v \\ y = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 \end{bmatrix} \Delta v \end{cases} \quad (1)$$

Or in transfer function form

$$G(s) = \frac{\Delta v}{\Delta y} = \frac{k_1}{s(s^2 + k_2 s + k_3)} \quad (2)$$

where

$$k_1 = \frac{A\gamma RTK}{M}\left(\frac{1}{V_{10}} + \frac{1}{V_{20}}\right)$$

$$k_2 = \frac{\beta}{M} \quad (3)$$

$$k_3 = \frac{k}{M} + \frac{\gamma A^2}{M}\left(\frac{P_{10}}{V_{10}} + \frac{P_{20}}{V_{20}}\right)$$

2.2 Sliding mode control

Among various automatic control techniques, sliding mode has been considered as a robust control method which can exhibit a high control quality and provide a systematic design.

SMC is actually one kind of variable structure control systems. It is derived from variable structure control as a high-speed switched feedback control.

Sliding mode is a robust control approach which can efficiently handle nonlinear systems [4, 5]. Basically, the idea in designing SMC is using a discontinuous control action to direct state trajectories toward a prespecified hyperplane (sliding surface) in the state space, and to maintain state trajectories sliding on the hyperplane for subsequent time. The hyper plane is also called switching plane because the switched control signal switches its gain on this plane according to the value of the plant state. The switched control is derived from Lyapunov stability approach. The main properties of SMC are its insensitivity to disturbances, zero tracking error, and finite-time transient [6]. The key point for SMC gaining its precious characteristics is all system trajectories must be converged to sliding surface in a finite time and slide along this surface toward the desired state. Consider the second order system is described as below

$$\ddot{x}(t) = f(\dot{x}, t) + b(x,t)u(t) + d(t) \quad (4)$$

With these following assumptions

$$0 < b_{\min} \le b(x,t) \le b_{\max} \quad (5)$$

$$\left|\tilde{f}(x,t) - f(x,t)\right| \le F(x,t) \quad (6)$$

$$|d| \le D \quad (7)$$

Where $\tilde{f}(x,t)$ is the estimation of $f(x,t)$

Define $\tilde{b} = \sqrt{b_{\min} b_{\max}}$ and $\beta = \sqrt{b_{\max}/b_{\min}}$

With the reference output $x_d(t)$, the tracking error signal and its derivative are written as $e(t) = x(t) - x_d(t), \dot{e}(t) = \dot{x}(t) - \dot{x}_d(t)$. The sliding surface is specified as

$$s(e,t) = \left(\frac{d}{dt} + \lambda\right)e = \dot{e} + \lambda e \quad (8)$$

A suitable Lyapunov function candidate is $V(x) = \frac{1}{2}s^2$.

The reaching condition can be obtained

$$\dot{V} = \frac{1}{2}\frac{d}{dt}s^2 = s\frac{ds}{dt} \le -\eta|s| \quad (\eta > 0) \quad (9)$$

The control law satisfied the condition (9) is in the form

$$u = u_{eq} + u_{sw} = \tilde{b}^{-1}(-\tilde{f} + \ddot{x}_d - \lambda \dot{e}) - \tilde{b}^{-1} K sign(s) \quad (10)$$

In which, equivalent control u_{eq} which is yielded from ideal sliding mode (s=0) can be translated as the filtered value of instantaneous switching control action across sliding surface, switching control u_{sw} plays a very important role is to deal with system uncertainties and unmodeled high frequency term. The value of K is selected such that

$$K \geq (b^{-1}\tilde{b} - 1)\,|\,\tilde{f} - \ddot{x} + \lambda \dot{e}\,| + b^{-1}\tilde{b}\left[(f - \tilde{f}) + d + n\right] \quad (11)$$

Once control law (10) is properly designed, system states will be forced to hit sliding surface after a finite time.

In order to gain tracking performance, SMC employs infinite switching frequency, however in the real world; switched controller has imperfections that limit switching frequency to a finite value. The phenomenon describes the finite switching frequency and finite amplitude oscillation of the sliding mode is called chattering phenomenon. During the chattering, the control signal changes rapidly, if this phenomenon is not controlled, it may damage system devices. The most popular method to reduce chattering is introducing a saturation function $sat(s)$ instead of signum function in (10)

$$sat(s) = \begin{cases} 1 & when\ s > \phi \\ \dfrac{s}{\phi} & when\ -\phi \leq s \leq \phi \\ -1 & when\ s \leq -\phi \end{cases} \quad (12)$$

By using saturation function, there is existence of boundary layer covering the sliding surface. ϕ, a positive design parameter, is defined as a thickness of boundary layer. This reducing chattering technique tends to track desired states within a predefined precision $\varepsilon = \dfrac{\phi}{\lambda^{n-1}}$.

$$\left|e^{(i)}(t)\right| \leq (2\lambda)^i \varepsilon \quad (13)$$

When designing SMC, the boundary thickness must be appropriately adjusted to compromise between chattering level and tracking performance.

III. CONTROL SYSTEM FORMULATION

3.1 System identification

When the mathematical model was derived, the parameters of this model must be identified. To identify system parameters, a set of input/output experimental data is used. This means some experiments are performed by applying an input sequence and measuring the corresponding output sequence response. From these input and output responses, the model of dynamic system will be figured out.

The set of input and output sequences should be divided into two separate parts, estimation and validation data. Estimation data is used to fit a model to data and validation data is used for model validation purpose. Aim to excite all relevant frequencies of the system and receive a good model, Pseudo-Random Binary Sequence (PRBS) input always is a good choice in system identification. In this work, Matlab Identification Toolbox was utilized to work out the desired parameters, with given pneumatic mathematical model, the matching level between actual data and simulated data was not good. This means the given mathematical model should be slightly modified to match the real system. The model below provides a considerate matching level between theoretical and actual data.

$$G(s) = \frac{\Delta u}{\Delta y} = 86{,}248 \frac{(-18{,}178s + 1)}{s(9{,}118s^2 + 63{,}224s + 1)} \quad (14)$$

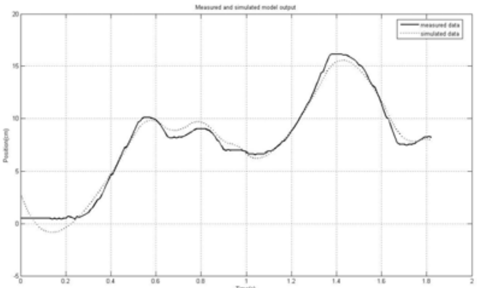


Fig. 1 Estimation data

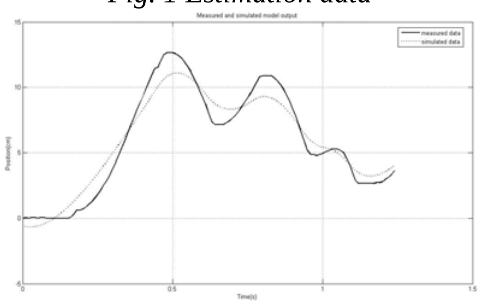


Fig. 2 Validation data 1

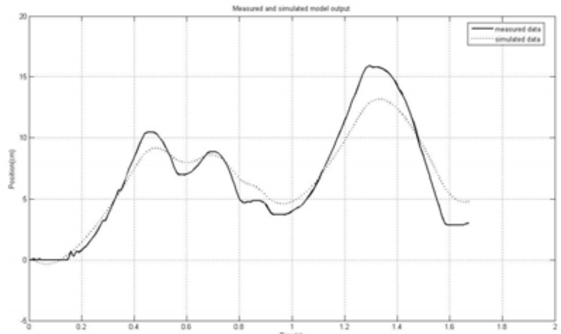


Fig. 3 Validation data 2

3.2 Multimode SMC-PID

The sliding surface for third order system is defined as follow

$$s(e,t)=\left(\frac{d}{dt}+\lambda\right)^2 e=\lambda^2 e+2\lambda\dot{e}+\ddot{e}=0 \quad (15)$$

For simplifying SMC, only the switching control term in SMC law is applied. The control signal is given by

$$u=-Vsign(s) \quad (16)$$

V is strictly positive and selected as the maximum voltages that is feed to the proportional valve (5 Volts). To reduce chattering, (16) is rewritten as

$$u=-Vsat(\frac{s}{\phi}) \quad (17)$$

When applying a boundary layer, there is a tradeoff between the smoothness of control signal and control accuracy. This tradeoff leads to the combination of sliding mode and another control technique. The added control technique which is activated inside the boundary region targets to enhance tracking error.

PID controller is proved as a control law that can provide a good performance in steady state. By fine tuning PID parameters, zero tracking error can be archived.

Through the investigation of the advantages and disadvantages of PID and SMC, a control law that takes advantages of these two controllers can be described below

$If\,(|e|\geq E_m)$ then control mode = SMC else control mode=PID

Where E_m is the tracking error threshold.

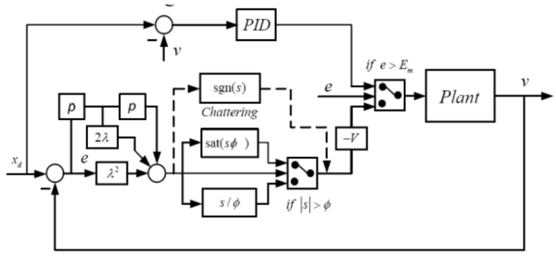


Fig. 4 Multimode SMC-PID scheme

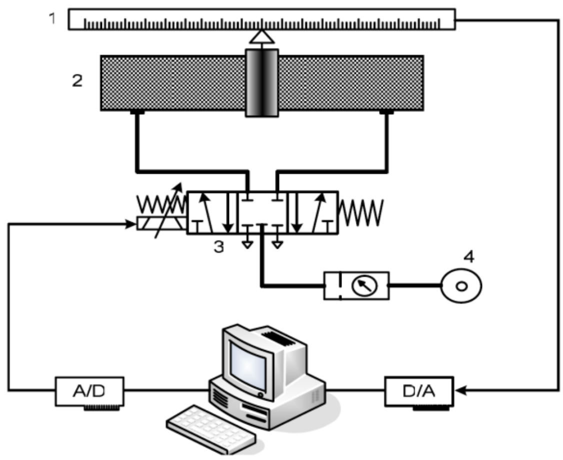
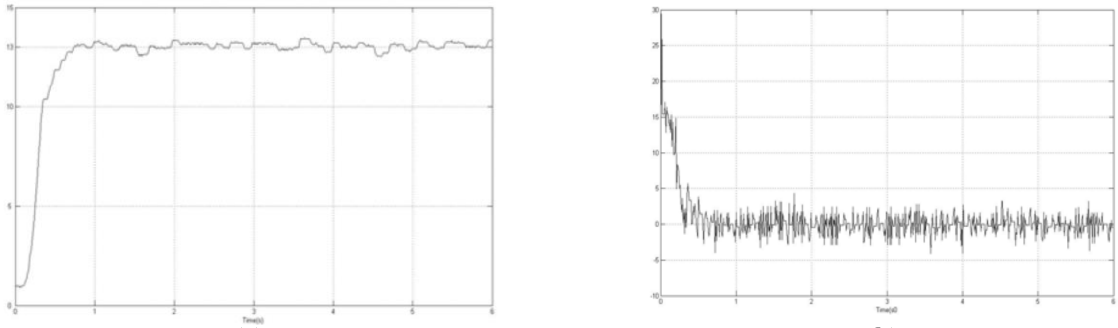


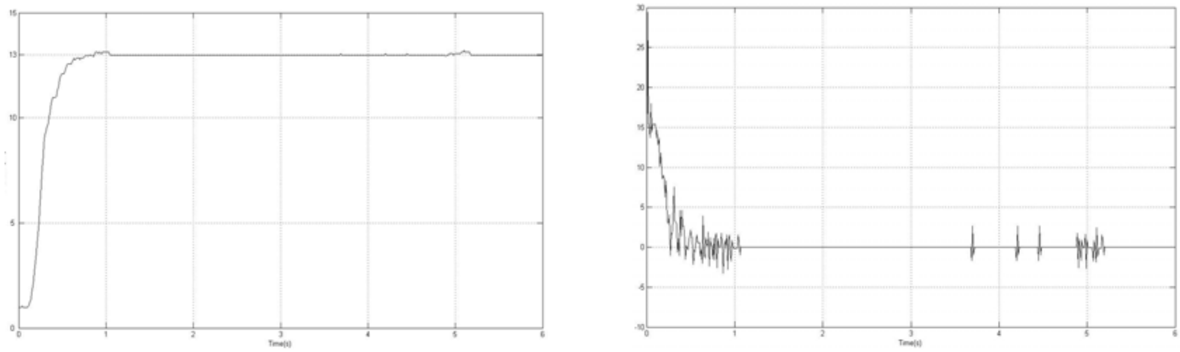
Fig. 5 Experiment setup

The experiment setup is composed of a pneumatic system, a data acquisition board, a linear potentiometer. Pneumatic system contains a magnetically coupled rodless cylinder, a 5-way 3-state proportional control valve, and an air compressor with nominal pressure of 4bar. In practical application, a pressure feedback is used instead of acceleration feedback because acceleration feedback is expensive. In this work, the actual position is recorded by a potentiometer; the first and second order time derivatives of piston position are considered as velocity and acceleration information respectively.



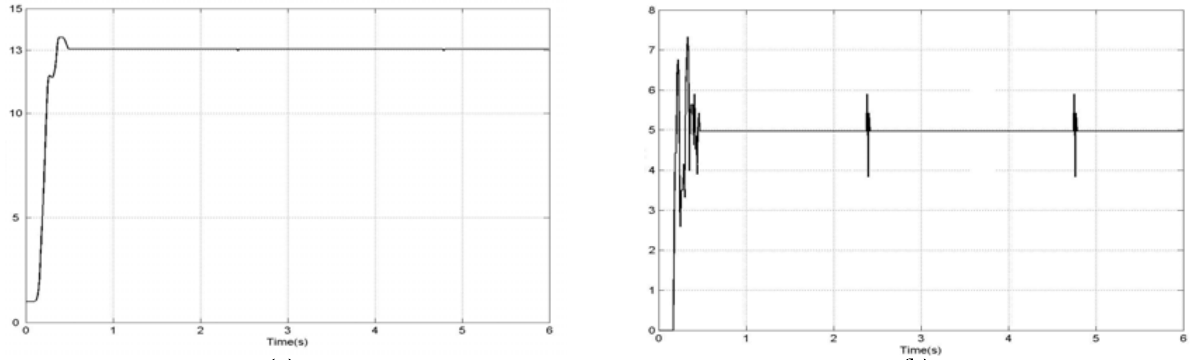
(a) (b)

Fig. 6 System responses of SMC with signum function (a) Position response (b) Sliding surface



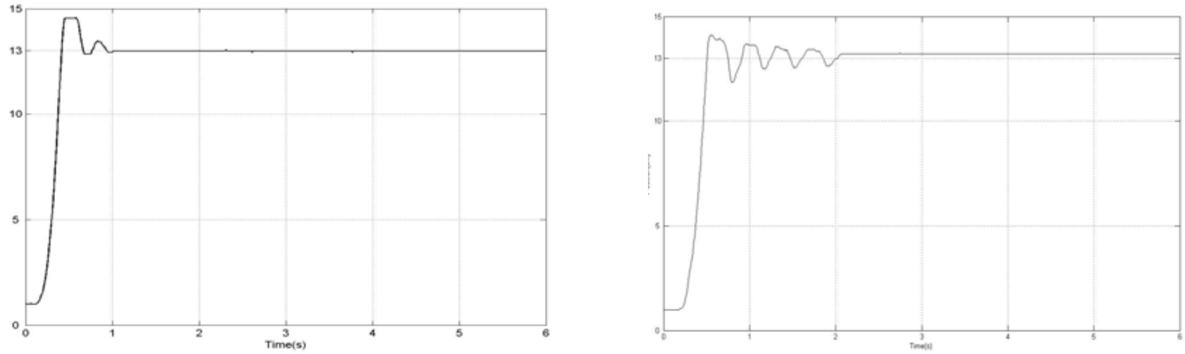
(a) (b)

Fig. 7 System responses of SMC with saturation function (a) Position response (b) Sliding surface



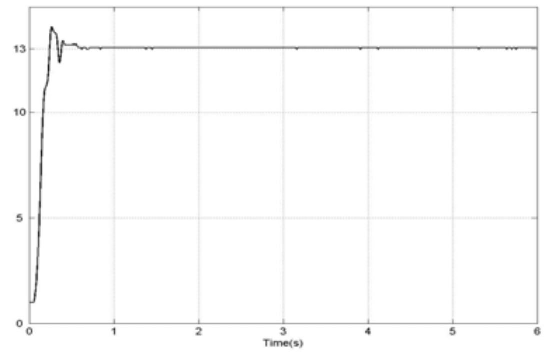
(a) (b)

Fig. 8 System responses of SMC-PID (a) Position response (b) Control output

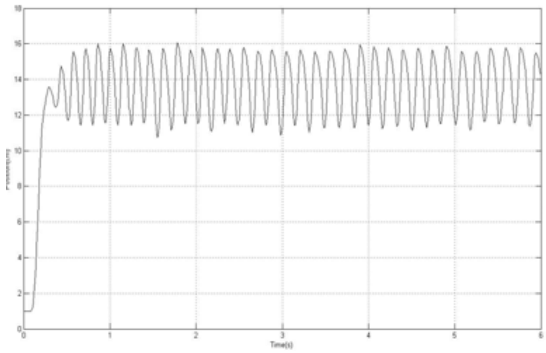


(a) (b)

Fig. 9 System responses when applying load of 3kg (a) SMC-PID (b) PID



(a)



(b)

Fig. 10 System responses with pressure supply of 8ba (a) SMC-PID (b) PID

The experimental results showed that chattering is obvious when introducing signum function in SMC. However, using saturation function can considerably reduce chattering phenomenon. The role of boundary layer in saturation function is important because it affects the relation between control smoothness and position accuracy.

Multimode SMC-PID controller response indicates that it can reduce chattering and also guarantees the robustness of the control system. In comparison with conventional SMC, multimode SMC-PID has a lower chattering level in control output, and when compared to PID controller, it is superior in term of robustness.

IV. CONCLUSIONS

Sliding mode gains robustness by using discontinuous control law across sliding surface, due to this reason, sliding mode suffers from chattering phenomenon. In conventional SMC, to reduce chattering phenomenon, discontinuous control signal's signum function is replaced by a saturation function in a small vicinity of sliding surface. The existence of saturation function results in constrain between the smoothness of control law and the tracking performance.

In order to smooth out control signal and eliminate nonzero tracking error, a multimode PID-SMC controller is proposed. The switching value that used to switch between two controllers is a predefined small threshold error. If the actual error is greater than threshold value, SMC is activated otherwise, PID is activated. This combination aims to take advantages of SMC in transient state and of PID control in steady state. Because of limitations in the accuracy of hardware model, zero tracking error performance can not be established by experiment.

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