J. Automation & Systems Engineering 9-2 (2015): 132-143

Regular paper

High Gain Observer Applied to a Sliding Mode Control for Pneumatic Actuator

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Journal of Automation & Systems Engineering

Abstract- *Nonlinear control laws become the most important strategies to control electropneumatic actuator. To get high accuracy and performance, we need the knowledge of all state variables. This paper focus on the design of high gain observer that estimates the unmeasured states (velocity and pressure in chamber N) from the measurements of the position and pressure in chamber P. It is characterized by its simplicity and implementation capability. Simulations results are presented to test the effectiveness of our high gain observer, which is applied to sliding mode controller in order to control tracking position and pressure.*

Keywords: Electropneumatic Actuator, High Gain Observer, Sliding mode control.

1. INTRODUCTION

PNEUMATIC control systems have become the focus of several research due to their complexity and the presence of non-linearities. The first classical controller applied to the electropneumatic system is a fixed-gain linear controller based on the local linearization of the nonlinear dynamics about a nominal operating point [1]. However, it has the inconvenient of the limitation of the linear feedback controller for the nonlinearities adverse effect or parameter variations. Thus, many research have developed in the nonlinear control such as feedback linearization [2], fuzzy control algorithms [3], adaptive control [4], robust linear control [5], robust differentiator controller [6], sliding mode control ([7], [8]) and higher sliding mode control([9], [10]).

The standard sliding mode features are high accuracy and robustness with respect to various internal and external disturbances. Specific drawback due to the classical sliding mode techniques is the chattering phenomenon. The chattering phenomenon is generally perceived as motion, which oscillates around the sliding manifold. In this paper, a sliding mode controller designed in [11] is used. The reaching law method is applied on a PD sliding surface form in order to reduce the chattering phenomenon and to minimize the tracking error. However, for the application of such control laws, all the state variables must be known. In fact, the position measurement is still available and the pressure is not systematically. Therefore, we need an observer to reduce the number of sensors and to evaluate the disturbance. The observation has several advantages such as disturbance reconstructing to increase the robustness and removing one of pressure sensors to reduce the manufacturing cost. Very few works have made in observation. Only observability property has been studied in [12]. High gain and sliding mode observers are developed in [13], The gain of the proposed observer involves the computation of the jacobian inverse.

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The originality of the current papers is to construct a state observer for a class of MIMO nonlinear system under similar assumptions. The main characteristics of the proposed observer lies in its simplicity and its capability in implementation which it does not need the inversion of any jacobian transformation.

The paper is organized as follow. In section 2, we present the model of the electropneumatic system. Section 3 is devoted to observer's design where we give the class of the nonlinear MIMO system and the observer under investigation. The high gain observer applied to our system is given in section 4. The simulation results are presented to show the effectiveness of our observer in section 5. In the last section, we present some conclusions.

2. ELECTROPNEUMATIC MODEL

The electropneumatic system under interest is a double acting actuator (Fig.1) constituted by two chambers, denoted P (as positive) and N (as negative). The air mass flow rates entering the two chambers are modulated by two three-way servodistributors controlled by a micro-controller with two electrical inputs. The pneumatic jack horizontally moves a load carriage of mass M.

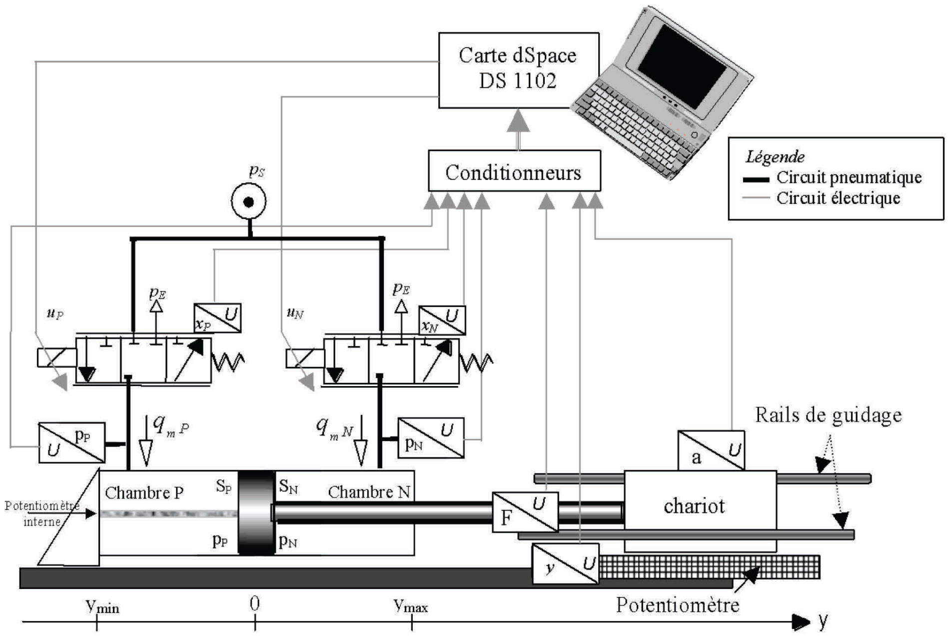

Fig. 1. Electropneumatic system

The electropneumatic plant model is obtained from three physical laws:

- the mass flow rate through a restriction,
- the pressure behaviour in a chamber with variable volume,
- the fundamental mechanical equation.

In our case, the bandwidths of the Servotronic Joucomatic servodistributor and actuator are, respectively, about 200 and 2, 4 Hz. Using the singular perturbation theory, the dynamics of the servodistributors are neglected and their model can be reduced to a static one, described by two relationships $q_{mP}(u_P, p_P)$ and $q_{mN}(u_N, p_N)$ between the mass flow rates q_{mP} and

q_{mN}, the input voltages u_P and u_N and the output pressures p_P and p_N. The pressure evolution law in a chamber with variable volume is obtained assuming the following assumptions [14]:

- air is a perfect gas and its kinetic energy is negligible,
- the pressure and the temperature are homogeneous in each chamber,
- the process is polytropic and characterized by a coefficient,
- the temperature variation is negligible with respect to average and equal to the supply temperature.

Therefore, the following relations give the model of the previous system:

$$\begin{cases} \dfrac{dy}{dt} = v \\ \dfrac{dv}{dt} = \dfrac{1}{M}[S_P p_P - S_N p_N - F_f(v) - F_{ext}] \\ \dfrac{dp_P}{dt} = \dfrac{krT}{V_P(y)}[q_{m^P}(u_p, p_P) - \dfrac{S_P}{rT} p_P v] \\ \dfrac{dp_N}{dt} = \dfrac{krT}{V_N(y)}[q_{m^N}(u_N, p_N) + \dfrac{S_N}{rT} p_N v] \end{cases} \tag{1}$$

Where

$$\begin{cases} V_P(y) = V_P(0) + S_P y \\ V_N(y) = V_N(0) - S_N y \end{cases} \quad \text{with} \quad \begin{cases} V_P(0) = V_{DP} + S_P \dfrac{l}{2} \\ V_N(0) = V_{DN} + S_N \dfrac{l}{2} \end{cases}$$

are the effective volumes of the chambers for the zero position and $V_{D[P or N]}$ are dead volumes present at each extremity of the cylinder.

The mass flow rate q_m is an algebraic function and is given as in [1]:

$$q_m(u, p) = \varphi(p) + \psi(p, sign(u))u \tag{2}$$

with $\varphi(p)$ is a polynomial function of the pressure and $\psi(p, sign(u))$ is a polynomial function of both the pressure and of the input control.

From (2) the nonlinear affine model is given by these following equations:

$$\begin{cases} \dfrac{dy}{dt} = v \\ \dfrac{dv}{dt} = \dfrac{1}{M}\left[S_P p_P - S_N p_N - bv - F_{ext}\right] \\ \dfrac{dp_P}{dt} = \dfrac{krT}{V_P(y)}\left[\varphi(p_P) - \dfrac{S_P}{rT} p_P v\right] + \dfrac{krT}{V_P(y)}\psi\left(p_P, \text{sgn}(u_P)\right)u_P \\ \dfrac{dp_N}{dt} = \dfrac{krT}{V_N(y)}\left[\varphi(p_N) + \dfrac{S_N}{rT} p_N v\right] + \dfrac{krT}{V_N(y)}\psi\left(p_N, \text{sgn}(u_N)\right)u_N \end{cases} \tag{3}$$

with two inputs u_P and u_N, the nonlinear model of the electropneumatic system has the following form :

$$\dot{\underline{x}} = f(\underline{x}) + g(\underline{x})\ U \qquad (4)$$

with $\underline{x} = \begin{bmatrix} y & v & p_P & p_N \end{bmatrix}^T$ and $U = \begin{bmatrix} u_P & u_N \end{bmatrix}^T$ are respectevely the state vector and the input control and $f(\underline{x})$ and $g(\underline{x})$ are nonlinear functions defined as follow :

$$f(x) = \begin{pmatrix} v \\ \frac{1}{M}[S_P p_P - S_N p_N - bv - F_{ext}] \\ \frac{krT}{V_P(y)}\left[\varphi(p_P) - \frac{S_P}{rT} p_P v\right] \\ \frac{krT}{V_N(y)}\left[\varphi(p_N) + \frac{S_N}{rT} p_N v\right] \end{pmatrix}$$

And

$$g(x) = \begin{pmatrix} g_1(x) & g_2(x) \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ \frac{krT}{V_P(y)}\psi\left(p_P, \mathrm{sgn}(u_P)\right) & 0 \\ 0 & \frac{krT}{V_N(y)}\psi\left(p_N, \mathrm{sgn}(u_N)\right) \end{pmatrix}$$

In the next section, we will specify the class of nonlinear system considered for the synthesis of the observer and we will present some assumptions which are necessary for the synthesis.

3. OBSERVERS DESIGN

3.1 Class of Nonlinear System

Consider the nonlinear MIMO systems :

$$\begin{cases} \dot{x} = f(u, x) \\ y = \bar{C}x = x^1 \end{cases} \qquad (5)$$

with

$$x = \begin{pmatrix} x^1 \\ x^2 \\ \vdots \\ x^{q-1} \\ x^q \end{pmatrix};\ f(u,x) = \begin{pmatrix} f^1(u, x^1, x^2) \\ f^2(u, x^1, x^2, x^3) \\ \vdots \\ f^{q-1}(u,x) \\ f^q(u,x) \end{pmatrix};$$

$$\bar{C} = \begin{pmatrix} I_{n1} & 0_{n1\times n2} & 0_{n1\times n3} & \dots & 0_{n1\times nq} \end{pmatrix}$$

We note that the state $x \in \mathbb{R}^n$ with $x^k \in \mathbb{R}^{n_k}$, $k = 1 \cdots q$ and $p = n_1 \geq n_2 \geq \cdots \geq n_q$; $\sum_{k=1}^{q} n_k = n$; the input $u(t) \in \mathcal{U}$ the set of bounded absolutely continuous functions with bounded derivatives from $\mathbb{R}^+$ into $\mathcal{U}$ a compact subset of $\mathbb{R}$; $f(u,x) \in \mathbb{R}^n$ with $f^k(u,x) \in \mathbb{R}^{n_k}$.

Our aim consists in design an observer for the system (5). Such a design needs some assumptions, which will be stated in due course.

3.2 Assumptions

At this step, one assumes the following :

A1. Each function $f^k(u,x)$, $k = 1 \cdots q-1$ satisfies the following rank condition :

$$rang\left(\frac{\partial f^k}{\partial x^{k+1}}(u,k)\right) = n_{k+1} \forall x \in \mathbb{R}^n ; \forall x \in U \qquad (6)$$

Moreover $\exists \alpha, \beta > 0$ such that for all $k = 1 \cdots q-1$, $\forall x \in \mathbb{R}^n ; \forall u \in U$,

$$\alpha^2 I_{n_{k+1}} \leq \left(\frac{\partial f^k}{\partial x^{k+1}}(u,k)\right)^T \left(\frac{\partial f^k}{\partial x^{k+1}}(u,k)\right) \leq \beta^2 I_{n_{k+1}}$$

where $I_{n_{k+1}}$ is the $(n_{k+1}) \times (n_{k+1})$ identity matrix.

A2. For $1 \leq k \leq q-1$; the function $x^{k+1} \rightarrow f^k(u, x^1, \ldots, x^k, x^{k+1})$ is one to one from $\mathbb{R}^{n_{k+1}}$ into $\mathbb{R}^{n_k}$.

Now, we propose to synthesize a nonlinear observer for system (5).

3.3 Observers Synthesis

The synthesis of this observer is based on uniform observability propriety of (5). The class of observer is interesting due its applicability to a large class of nonlinear systems.

A candidate observer for systems (5) is given by the following equation :

$$\dot{\hat{x}} = f(u,\hat{x}) - \theta \Lambda^+(u,\hat{x}) \Delta_\theta^{-1} S^{-1} C^T \bar{C}(\hat{x} - x) \qquad (7)$$

where $\hat{x} = \begin{bmatrix} \hat{x}^1 \\ \hat{x}^2 \\ \vdots \\ \hat{x}^q \end{bmatrix} \in \mathbb{R}^n$ with $\hat{x}^k \in \mathbb{R}^{nk}$, $k = 1, \ldots, q$.

$\Delta_\theta = diag\left[I_{n_1}, \theta^{-1} I_{n_1}, \ldots, \theta^{-(p-1)} I_{n_1} \right]$ where $\theta > 0$ is a real number.

S is the unique solution of the algebraic Lyapunov equation :

$$S + A^T S + SA - C^T C = 0 \qquad (8)$$

where $S^{-1} C^T = \left[C_q^1 I_p, \ldots, C_q^q I_p \right]^T$ with $C_n^p = \dfrac{n!}{(n-p)!\,p!}$ and $C = \left[I_{n1}, 0_{n1}, \ldots, 0_{n1} \right]$

$$\Lambda(u,\hat{x}) = diag\left[I_{n1}, \frac{\partial f^1}{\partial x^2}(u,x), \frac{\partial f^1}{\partial x^2}(u,x) \frac{\partial f^2}{\partial x^3}(u,x), \ldots, \prod_{k=1}^{q-1} \frac{\partial f^k}{\partial x^{k+1}}(u,x) \right]$$

$\Lambda(u,x)$ is a diagonal matrix and left invertible according to assumption (A1). We note $\Lambda^{+}(u,x)$ its left inverse.

Theorem. Consider systems (5) and (7). Then,

$\exists\theta_0>0;\forall\theta>\theta_0;\exists\lambda>0;\exists\mu_\theta>0;\ \forall u\in U;\forall\hat{x}(0)\in R^{n_1 q};$

we have :

$\|\hat{x}(t)-x(t)\|\le\lambda\theta^{q-1}e^{-\mu_\theta t}\|\hat{x}(0)-x(0)\|$

where $x(t)$ is the unknown trajectory of (5) associated to the input u, $\hat{x}(t)$ is any trajectory of system (7) associated to (u,y).

Moreover, we have $\lim_{\theta\to\infty}\mu_\theta=+\infty$.

Proof. The proof of this theorem is given in [15]

5. HIGH GAIN OBSERVER APPLIED TO ELECTROPNEUMATIC SYSTEM

The electropneumatic system given by (3) can be written as follow:

$$\begin{cases}\dot{x}_1=x_2\\ \dot{x}_2=\dfrac{1}{M}[S_Px_3-S_Nx_4-F_f(x_2)-F_{ext}]\\ \dot{x}_3=\dfrac{krT}{V_P(x_1)}[\varphi(x_3)-\dfrac{S_P}{rT}x_3x_2]+\dfrac{krT}{V_P(x_1)}\psi(x_3,u_P)u_P\\ \dot{x}_4=\dfrac{krT}{V_N(x_1)}[\varphi(x_4)+\dfrac{S_N}{rT}x_4x_2]+\dfrac{krT}{V_N(x_1)}\psi(x_4,u_N)u_N\end{cases}\tag{9}$$

with $x=\begin{bmatrix}x_1 & x_2 & x_3 & x_4\end{bmatrix}^T=\begin{bmatrix}y & v & p_P & p_N\end{bmatrix}^T$; $u=\begin{bmatrix}u_P & u_N\end{bmatrix}^T$ and $y=\begin{bmatrix}x_1 & x_3\end{bmatrix}^T$ are respectively the state, the input and the output vectors, where $x\in\mathbb{R}^4$, $u\in\mathbb{R}^2$ and $y\in\mathbb{R}^2$.

We note that only the position and pressure in chamber P is measured. In this Step, we put the system (9) in the form of class (5).

We define the new state vector : $x^1=\begin{bmatrix}x_1 & x_3\end{bmatrix}^T$, $x^2=x_2$ and $x^3=x_4$ and $f(u,x)$ a nonlinear function given as follow :

$$f(u,x)=\begin{pmatrix} f^1(u,x^1,x^2) \\ f^2(u,x) \\ f^3(u,x) \end{pmatrix}=\begin{pmatrix}\begin{pmatrix} x_2 \\ \frac{krT}{V_P(x_1)}[\varphi(x_3)-\frac{S_P}{rT}x_3x_2]+\frac{krT}{V_P(x_1)}\psi(x_3,u_P)u_P \end{pmatrix} \\ \frac{1}{M}[S_Px_3-S_Nx_4-F_f(x_2)-F_{ext}] \\ \frac{krT}{V_N(x_1)}[\varphi(x_4)+\frac{S_N}{rT}x_4x_2]+\frac{krT}{V_N(x_1)}\psi(x_4,u_N)u_N \end{pmatrix}$$

Therefore, the matrix $\Lambda(u,x)$ can be deduced **:**

$$\Lambda(u,x)=diag\left[I_{n1},\ \frac{\partial f^1}{\partial x^2}(u,x),\frac{\partial f^1}{\partial x^2}(u,x)\frac{\partial f^2}{\partial x^3}(u,x)\right]$$

$$\Lambda(u,x)=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{kS_Px_3}{V_P(x_1)} & 0 \\ 0 & 0 & 0 & -\frac{S_N}{M} \\ 0 & 0 & 0 & \frac{kS_PS_Nx_3}{MV_P(x_1)} \end{bmatrix}$$

We define Λ^+ the left invertible matrix of Λ by the following expression: $\Lambda^+=(\Lambda^T\Lambda)^{-1}\Lambda^T$ **.**

A high gain observer for (9) is defined as:

$$
\begin{cases}
\dot{\hat{x}}_1 = \hat{x}_2 - 3\theta\tilde{x}_1 \\
\dot{\hat{x}}_2 = \dfrac{1}{M}[S_P\hat{x}_3 - S_N\hat{x}_4 - F_f(\hat{x}_2) - F_{ext}] - \dfrac{3\theta^2}{1+\left(\dfrac{kS_P\hat{x}_3}{V_P(\hat{x}_1)}\right)^2}\left[\tilde{x}_1 - \dfrac{kS_P\hat{x}_3}{V_P(\hat{x}_1)}\tilde{x}_3\right] \\
\dot{\hat{x}}_3 = \dfrac{krT}{V_P(\hat{x}_1)}[\varphi(\hat{x}_3) - \dfrac{S_P}{rT}\hat{x}_3\hat{x}_2] + \dfrac{krT}{V_P(\hat{x}_1)}\psi(\hat{x}_3, u_P)u_P - 3\theta\tilde{x}_3 \\
\dot{\hat{x}}_4 = \dfrac{krT}{V_N(\hat{x}_1)}[\varphi(\hat{x}_4) + \dfrac{S_N}{rT}\hat{x}_4\hat{x}_2] + \dfrac{krT}{V_N(\hat{x}_1)}\psi(\hat{x}_4, u_N)u_N \\
\quad - \dfrac{\theta^3}{\left(\dfrac{S_N}{M}\right)^2 + \left(\dfrac{kS_PS_N\hat{x}_3}{MV_P(\hat{x}_1)}\right)^2}\left[-\dfrac{S_N}{M}\tilde{x}_1 + \dfrac{kS_PS_N\hat{x}_3}{MV_P(\hat{x}_1)}\tilde{x}_3\right]
\end{cases} \tag{10}
$$

where θ is the gain of the observer.

Simulations and results

The controller used in the following simulations is a sliding mode controller designed in [11]. It ensures a good tracking for both actuator's position and pressure in chamber P and it reduces the chattering phenomenon.

The proposed sliding surface; $\sigma_i\,(i = 1,2)$ defined as:

$$
\begin{cases}
\sigma_1 = k_1e_y + k_2e_v + k_3e_a + k_4\dot{e}_a \\
\sigma_2 = k_5e_p + k_6\dot{e}_p
\end{cases} \tag{11}
$$

with

$$
\begin{cases}
e_y = y - y^d \\
e_v = v - v^d \\
e_a = a - a^d \\
e_p = p_P - p_P^d
\end{cases}
$$

y^d, v^d, a^d and p_P^d are respectively the position, velocity, acceleration and pressure desired trajectories and k_i are positives constants with $i = 1,\ldots,6$.

The reaching law is a differential equation which specifies the dynamics of a switching function σ_i . It was selected as follows :

$$
\dot{\sigma}_i = -\eta(\sigma_i + \omega\,\mathrm{sign}\sigma_i) \tag{12}
$$

with η and ω are positives constants.

The existence condition of sliding mode implies that both σ_i and $\dot{\sigma}_i$ will tends to zero when t tend to infinity, which means that the dynamic of the system will stay into the sliding surface. The existence condition of the sliding mode is $\sigma_i \dot{\sigma}_i < 0$.

The control law given in [11] is deduced by the derivation of sliding surface. One has

$$[\dot{\sigma}_1 \quad \dot{\sigma}_2]^T = F(x) + G(x)[\dot{u}_P \quad \dot{u}_N]^T \tag{13}$$

We note that $G(x)$ is an invertible matrix thus there are no singularity in the control law

$$[\dot{u}_P \quad \dot{u}_N]^T = G(x)^{-1}\left[F(x) + [\dot{\sigma}_1 \quad \dot{\sigma}_2]^T\right] \tag{14}$$

The control needs the knowledge of all state variables that implies, in the current case, the use of an observer. The initial actual and estimated conditions have the following values: $x_1(0) = -0.12m$, $\hat{x}_1(0) = 0.0m$, $x_2(0) = 0.0m/s$, $\hat{x}_2(0) = 0.0m/s$, $x_3(0) = 3bar$, $\hat{x}_3(0) = 2bar$, $x_4(0) = 3bar$, $\hat{x}_4(0) = 1bar$ and the gain of the observer is $\theta = 80$.

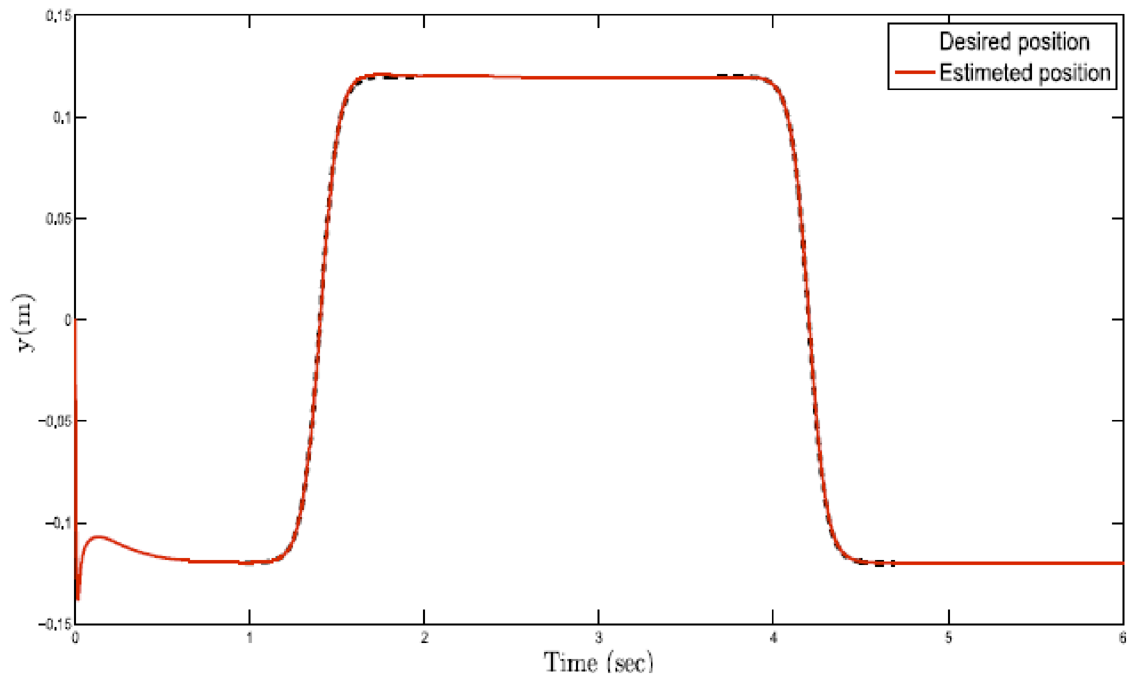

Fig. 2. Desired and estimated position (m)

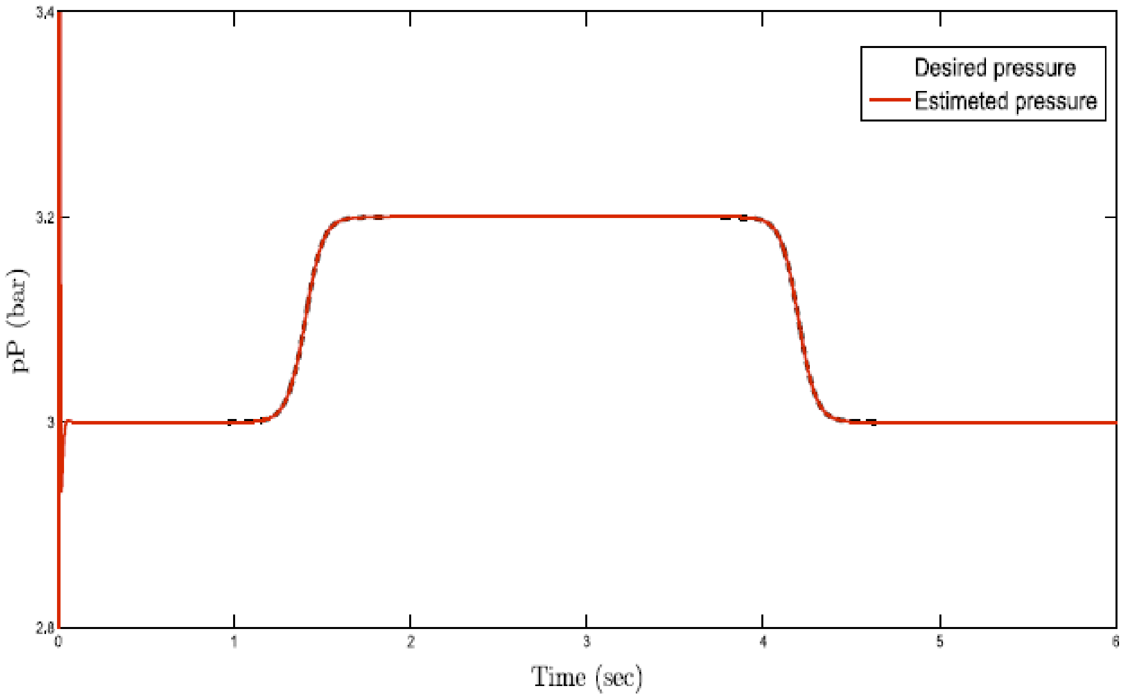

Fig. 3. Desired and estimated pressure in chamber P (bar).

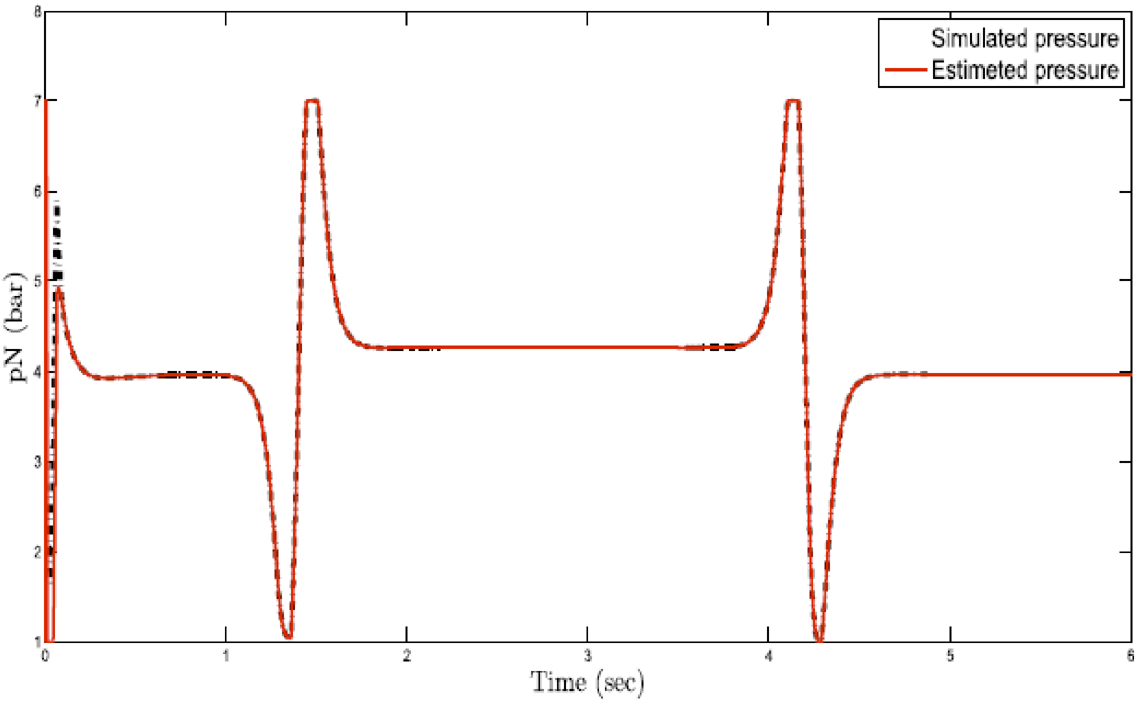

Fig. 4. Simulated and estimated velocity (m/s).

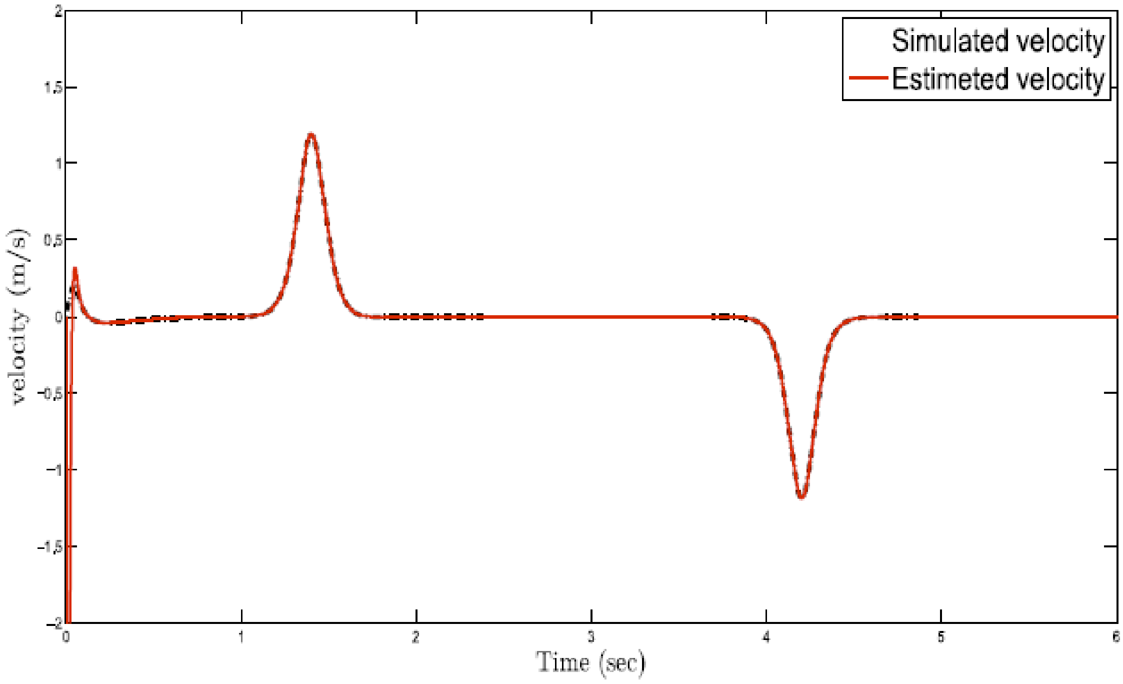

Fig. 5. Simulated and estimated pressure in chamber N (bar).

Fig.2 and Fig.3 shows the applicability and the efficiency of the control law coupled to observer (7) since we obtained good tracking responses of position and pressure in chamber P. Estimated results are reported in Fig.4 and Fig.5 where they are compared to the true value (obtained by the model of simulation). Fig.4 and Fig.5 clearly show the good performance of the proposed observer. Indeed, we remark a good agreement between simulated and estimated curves beyond 0.1s. This observer is advisable since its setting depends on only one parameter synthesis θ.

6. CONCLUSIONS

High gain observer is designed for electropneumatic system. It characterized by the implementation simplicity. This proposed observer is applied to sliding mode controller to control actuator and pressure in chamber P. The reaching law method is applied on a PD sliding surface form in order to reduce the chattering phenomenon and to minimize the tracking error. Simulation results are presented to show the applicability and the high accuracy of our observer. Future work concern to evaluate this observer in experimentation and to compare it with dynamic high gain observer.

ACKNOWLEDGMENT

This work was supported by the Ministry of Higher Education and Scientific Research of Tunisia

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