Pneumatic Cylinder Control for a Flexible Manipulator Robot

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***Abstract*— This work shows the development of a pneumatic cylinder controller that due to compressibility air characteristics presents a non linear behavior. The development includes a PID and a discrete PID approximation as solution to the problem. The presented development is part of a Flexible Manipulator Robot with dielectric characteristics for porcelain isolator cleaning of high voltage transmission lines, with one freedom degree. A simplified Thermo-Mechanics model has been developed for manipulator control simulation. This paper shows an alternative control proposal, and results to implement it.**

I. Introduction

THE idea to develop a flexible manipulator robot with pneumatic actuator, comes from the necessity of porcelain isolator clearing of high voltage transmission lines [1], without a personal high risk.

However, most of manipulators robots use an electric or hydraulic actuators, but the pneumatic actuators have not been used. This work consider the conjunction of flexible manipulators and electropneumatic control.

This is the beginning of a project which involves the use of a pneumatic cylinder to control a flexible manipulator robot. Our first approach is to use one degree of freedom, but the main goal is to have a two degree of freedom flexible manipulator.

Pneumatic cylinders are very useful for its clean, economy and low weight; however, due to air compressibility and internal friction, they present a highly non linear behavior [2]. Because of these conditions, there are certain difficulties in pneumatics cylinder control design.

Several pneumatic controllers has been developed; for example, the Model Reference Adaptive Control, MRAC [3]; however, the pneumatic model used for the control design, have the next considerations: a lineal actuator, a lineal valve, without damping systems at the sides, ideal gas, adiabatic changes and constant viscous friction.

Other works have been focused in friction parameter identification techniques of cylinder pneumatic [4], dynamic modeling and simulation [5], analytic and experimental research [6] and the development of robotic hands using cylinder pneumatics.

Flexible manipulators are ligth, cheap and have a higher power-weight relation robot. This kind of robot must be used only under two conditions: When the robot weight must be minimized, and when collisions in the work space must be prevented [7]. The modeling of flexible manipulators have been developed almost 35 years ago [8] [9], where, almost in all cases, they used electric or hydraulic actuators, and pneumatic cylinders are discouraged because of their non linear behavior.

Pneumatic control started in 1968, with Burrows [10], and present works have relation with adaptive control methods [3] [11], where some of them use a computer to implement the control [12]. Other works have been working in mechanical systems modeling with pneumatic actuators [13], from these kind of works, it has been developed the Flexible Manipulator Model with pneumatic cylinder, called Thermo-Mechanical model, where the mechanical system is involved to give the movement for the flexible arm [14].

By other hand [15], electric actuators are used for the development of flexible manipulators where the motor speed is considered for the control law implementation along with the motor effects and the system structure.

In our system we are using a flexible manipulator robot with a pneumatic actuator, where we consider the damping systems in both sides and the mechanical dynamics for control. The full Thermo-Mechanical model [13] is used as a starting point, later it is simplified and the results are used for the control development. The main contribution of this work is the position control of a flexible manipulator using a pneumatic actuator and a simplified Thermomechanical model.

The integral Thermo-Mechanical model of pneumatic actuators allows to predict its behavior, considering the air compresibility effects, internal friction forces, damping effects in both extremes of the cylinder, massic flow and

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energy conservation; and gives us the instant pressure, that depends on rod position.

From the engineering control point of view, this model let us predict the variable behavior, envolved in the physical process, and can be used for control purposes.

II. Actuator Modelling

How we talk previously, the full Termo-Mechanical model was developed in [17], without a control proposal. Therefore, the work shows three control proposals, using PID, discrete PID and fuzzy logic algorithms.

Due to the high complexity of the Thermo-Mechanical model, the first step was to obtain a polynomial system equations to minimize the mathematical computing time. The model simplified are shown in the set of equations (1) to (10), previously developed [15].

For the interval $0 \le X \le L$:

$$\dot{X} = \frac{d}{dt} X \tag{1}$$

$$D\dot{X} = \frac{d^2}{dt^2} X \tag{2}$$

For the interval $0 \le X \le L_{alp}$

$$\dot{P}_{a1} = g_{21}(X)\left(\dot{m}_{a1} - \dot{m}_{c1} - 9.176\times10^{-10} P_{a1} DX\right)\times10^{8} \tag{3}$$

$$\dot{P}_{c1} = g_{31}(X)\left(\dot{m}_{c1} - 3.608\times10^{-8} P_{c1} DX\right)\times10^{6} \tag{4}$$

For the interval $L_{alp} < X \le L$

$$\dot{P}_{a1} = g_{22}(X)\left(\dot{m}_{a1} - 3.7\times10^{-8} P_{a1} DX\right)\times10^{11} \tag{5}$$

$$\dot{P}_{c1} = g_{32}(X)\left(\dot{m}_{c1} - 3.7\times10^{-8} P_{c1} DX\right)\times10^{11} \tag{6}$$

For the interval $0 \le X \le (L-L_{alv})$

$$\dot{P}_{c2} = g_{41}(X)\left(\dot{m}_{c2} + 3.469\times10^{-8} P_{c2} DX\right)\times10^{11} \tag{7}$$

$$\dot{P}_{a2} = g_{51}(X)\left(\dot{m}_{a2} + 3.469\times10^{-8} P_{a2} DX\right)\times10^{11} \tag{8}$$

For the interval $(L - L_{alv}) < X \le L$

$$\dot{P}_{c2} = g_{42}(X)\left(\dot{m}_{c2} + 3.352\times10^{-8} X_4 X_6\right)\times10^{13} \tag{9}$$

$$\dot{P}_{a2} = g_{52}(X)\begin{bmatrix} 9.983\times10^{3}\left(\dot{m}_{a2} - \dot{m}_{c2}\right) + \\ 1.168\times10^{-5} X_5 X_6 \end{bmatrix}\times10^{4} \tag{10}$$

For Termo-Mechanical solution, internal friction force, kinematic and dynamic model must be considered [17], and is showed in eq. (11) to (14).

$$F_{sv} = K_v \dot{X} + K_c \,\mathrm{sgn}(\dot{X}) + \frac{K_e\left(\frac{2}{\pi}\right)\arctan(\beta\dot{X})}{1+\delta\left|\dot{X}\right|} \tag{11}$$

$$F_a = p_1 A_p - p_2(A_p - A_v) - F_{sv} \tag{12}$$

$$\frac{d}{dt} p_i = F_i \qquad \frac{d}{dt} H_{Gi} = M_{Gi} \qquad i = 2,3,\ldots,6 \tag{13}$$

$$Rf = d \tag{14}$$

To solve the Thermo-Mechanical Model, the eq. (2) needs the system acceleration, that is given by eq. (14) where *R*, *d* and *f*, have the mechanical geometric information, dynamic information and variables to determine, respectively.

The pneumatic cylinder is installed on a mechanical system [13], as shown in Fig. 1, to generate the movement of the arm manipulator.

The output of the mechanic-pneumatic system is the arm elevation angle, θ_6, generated for the impulse mechanism, and depend of X rod displacement.

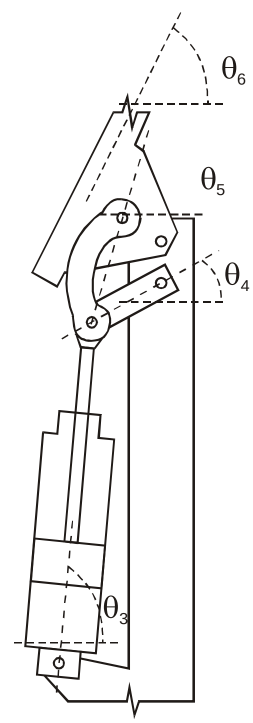

Fig. 1. Mechanical-Pneumatic system for the flexible manipulator.

III. Controller Modeling

The Thermo-Mechanical Model have as control inputs: the valve effective area air flow, (15).

$$u = [A_1, A_2, A_3] \tag{15}$$

Where A_1, A_2 and A_3 are the valve area of cylinder side, rod side, and air return, respectively.

A. *Controller PID Proposal*

Figure 2 shows the control block diagram used for the pneumatic actuator system, taking the θ angle as the mechanical system output.

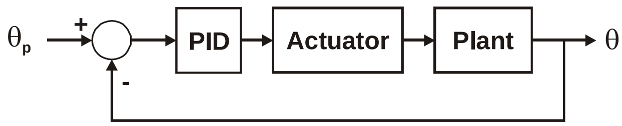

Fig. 2. Position Controller of manipulator arm with pneumatic actuator.

Equation (16), shows the error equation, integral error in (17) and derivative error in (18); the equation (19) shows control equation.

$$e = X_p - X \quad (16)$$

$$e_i = \sum_i e(T_i) \quad (17)$$

$$e_d = e(T_i) - e(T_{i-1}) \quad (18)$$

$$A_j = K_p e + K_i e_i + K_d e_d \quad (19)$$

Where X_p is rod position; X is actual rod position; T is time sample; $j=1,2,3$ for valve number; e, e_i y e_d are error signal for actual, integral and derivative control, respectively.

B. Discrete PID Control Proposal

Position PID discrete control [16], is described in equation (20).

$$u(t) = K_p \left[\begin{array}{l} e(t) + \frac{T_c}{T_i} \sum_{i=1}^{t} e(i) + \\ + \frac{T_d}{T_c} \left[e(t) - e(t-1) \right] \end{array} \right] + u(0) \quad (20)$$

Where *u(t)* is control variable; *u(0)* es initial position; K_p is the gain; T_j is integral time; T_d is derivative time and T_c is the control period.

C. Control using Speed Change Feedback

Due to the speed behavior, a mechanical vibration problem can appear in our system, and it is necessary to involve the speed change in the control algorithm. The hypothesis is that when we use a speed change feedback the behavior of the position control for the system will come soft, without risk of mechanical vibrations and the position result will be better.

A speed change feedback is added to the system control, as shown in figure 3.

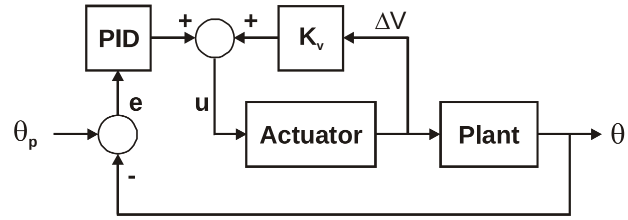

Fig. 3. Position controller of flexible arm impulse mechanism with speed change feddback.

The equations controller are shown in (21) to (22).

$$\Delta V = V_{nT} - V_{(n-1)T} \quad (21)$$

$$A_i = A_{i0} + Kp_{Ai} e + Ki_{Ai} \sum_{j=1}^{3} e_i + Kd_{Ai} e_d + Kv \Delta V \quad (22)$$

Where ΔV is the speed changes between nT and (n-1)T time samples; A_i is the valve aperture corresponding to i; Kp, Ki, Kd and Kv, are constants for proportional, integral, derivative control, and speed change, respectively.

With the speed change feedback, is eliminated the vibration problem and we get a better result for position control.

IV. Results

A. Controller PID

At start point, a Ziegler-Nichols classic method was used and the fine adjustment to improve the constant control values was doing in a heuristic way.

The constants values for the PID control are shown in table 1. Figure 4 shown control mechanism out angle, using differents values for reference, and figure 5 shown rod speed behavior. In figure 5 we can see instant speed change, and that is a problem because mechanical vibration effects can appear.

TABLE I
CONTROL VALUES USED FOR THE MECHANICAL-PNEUMATIC SYSTEM.

Valve	Kp	Ki	Kd
A_1	4.00	0.0	100.0
A_2	-4.00	0.0	-100.0
A_3	0.45	0.0	0.0

B. Discrete PID Controller

The values used are: Tc=0.5, Ti=10.0, Td= 12.5; the proportional control constants for A_1, A_2 y A_3, are 1.5, -1.5 and 9.5, respectively. Figure 6 shows the results of this kind of controller.

This control method have an angular speed behavior as shown in figure 7. For that, the vibration problem still present.

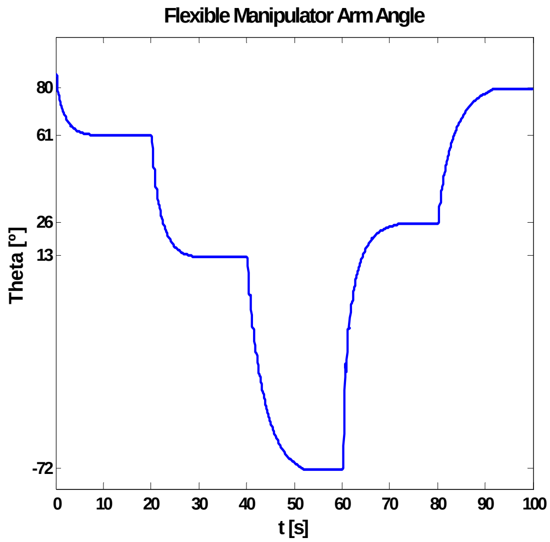

Fig. 4. Mechanical-pneumatic system with PID controller.

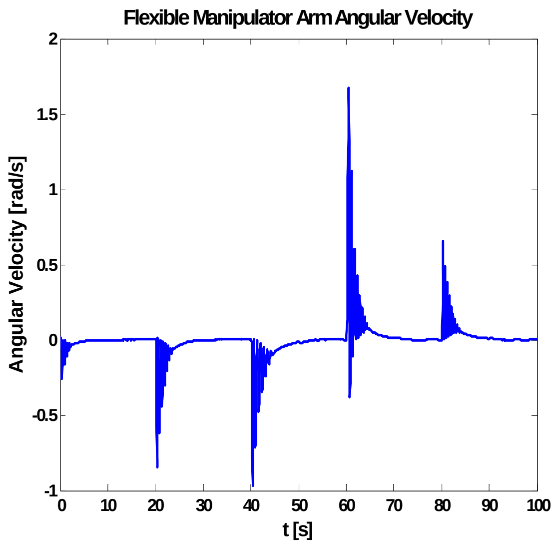

Fig. 5: Angular speed behavior with PID controller.

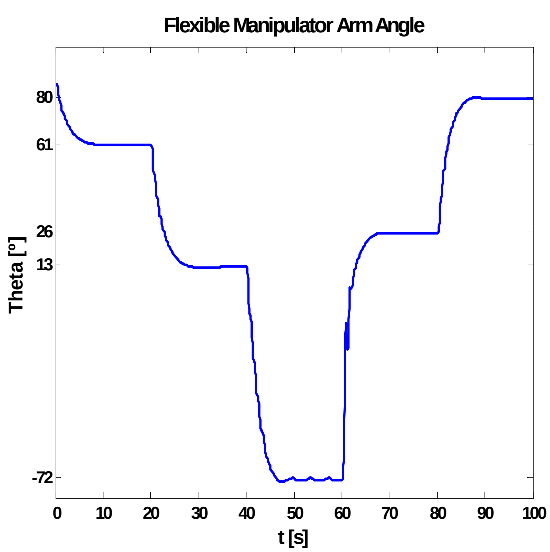

Fig. 6. Control mechanical-pneumatic system with discrete PID controller.

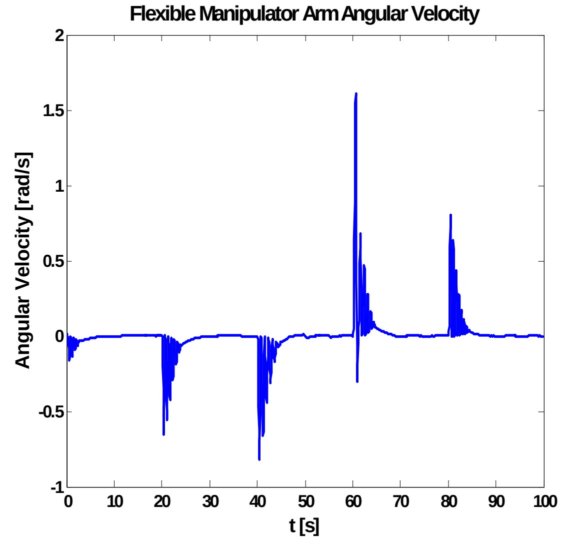

Fig. 7. Angular speed behavior with Discrete PID controller.

C. Result of Controller using Speed Change

The figure 8 shown the result of use speed change feedback control, and the table 2 give the values for the control constants.

Figure 9 shown angular speed graph, and we can see a smooth behavior, without instant changes, and the performance mechanical-pneumatic system is better than the PID controller.

TABLE I
VALUES USED TO THE DISCRETE PID CONTROL FOR MECHANIC-PNEUMATIC SYSTEM.

i	Kp, $\times 10^{-4}$		Ki $\times 10^{-4}$	Kd $\times 10^{-4}$	Kv
	S_p>-40	$S_p \leq$-40			
1	6.6	1.3	1	10	0.3
2	6.6	1.3	1	10	0.3
3	6.6	1.3	1	10	0.3

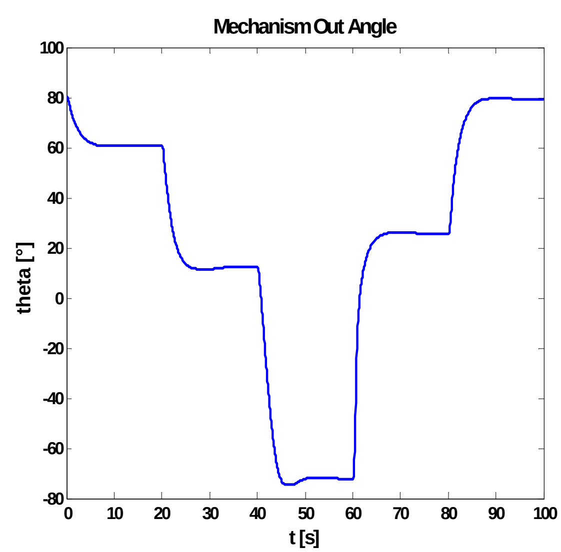

Fig. 8. Mechanical-pneumatic system with speed change feedback.

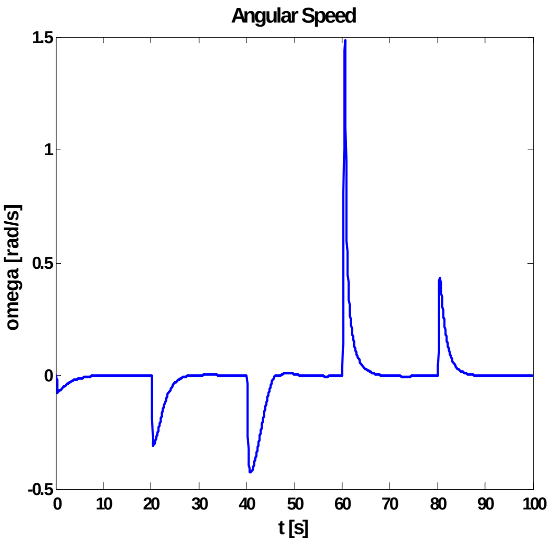

Fig. 9. Mechanical-pneumatic speed system with speed changes feedback controller.

V. Conclusions

As first approximation the position control for flexible manipulator was succesfull, with one degree of freedom, without vibration problem.

This work presented a position and speed control for flexible manipulator arm mechanism, with pneumatic actuator using the simplify Thermo-Mechanical model. The best results obtained is using speed change feedback, with a smooth behavior in the angle θ.

This results probe that it is possible to implement the speed change feedback algorithm control, to the mechanical-pneumatic system, with a smooth behavior.

As future work, is considering the use of reference frame, fuzzy logic, neuronal networks and maybe a combination of those controllers.

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