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Intelligently Tuned Weights Based Robust H_∞ Controller Design For Pneumatic Servo Actuator System With Parametric Uncertainty

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Abstract: This paper presents a new method for tuning the weighing functions to design an H_∞ controller. Based on a particle swarm optimization (PSO) algorithm the, weighting functions are tuned. The PSO algorithm is used to minimize the infinity norm of the transfer functions matrix of the nominal closed loop system to obtain the optimal parameters of the weighting function. This method is applied to a typical industrial pneumatic servo actuator controlled by a jet pipe valve. The pneumatic system nonlinearity and system parameters uncertainty are the main problems in the design of a desired controller for this plant. A linear model of the plant at certain operating point is derived and the structured (parametric) perturbations in the plant coeficients are taken into account. This method ensures an optimal robust stability and robust performance for the pneumatic servo actuator system. Simulation results are presented to verify the objectives of this method.

Key words: Robust control, H_∞ control, Pneumatic actuator, Nonlinear system, Uncertain system, PSO.

INTRODUCTION

A control system is robust if it remains stable and achieves certain performance criteria in the presence of possible uncertainties. The robust design is to find a controller, for a given system, such that the closed loop system is robust. The H_∞ optimization approach and its related approaches, being developed in the last two decades and still an active research area, have been shown to be effective and efficient robust design methods for linear, time invariant control systems (Da-Wei *et al*, 2005).

The goal of robust systems design is to retain assurance of system performance in spite of model inaccuracies and changes. A system is robust when it has acceptable changes in performance due to model changes or inaccuracies. A control system is robust when (i) it has low sensitivity, (ii) it is stable over the range of parameter variations and (iii) the performance continues to meet the specification in the presence of a set of changes in the system parameters (Dorf, 2001).

H_∞ is one of the most known techniques available nowadays for robust control. It is a method in control theory for the design of optimal controllers. Basically, it is an optimization method that takes into consideration a strong definition of the mathematical way to express the ability to include both classical and robust control concepts within a single design framework. It is known that H_∞ control is an effective method for attenuating disturbances and noise that appear in the system. It has been proven to be one of the best techniques in linear control system (Alok, 2007). Robust control techniques such as modern H_∞ and classical quantitative feedback theory (QFT) have received comparatively little attention in the fluid power literature, especially with regard to pneumatic systems (Mark and Nariman, 2004).

High performance position control of pneumatic actuators remains a difficult task. In most industrial applications, safety requires that the pressure of the air supply be kept low, which makes it difficult to design high bandwidth systems. Moreover, low supply pressure tends to limit the achievable actuator stiffness, which affects the ability of the servomechanism to reject disturbing loads. Nonlinear control valve flows and uncertainties in the plant parameters also complicate the design of high performance pneumatic servos. On the other hand, the pneumatic actuators are widely employed in position and speed control applications when cheap, clean, simple, and safe operating conditions are required. In recent years, low cost microprocessors and pneumatic components became available in the market, which made it possible to adopt more sophisticated control strategies in pneumatic system control (Jihong *et al*, 2007). The pneumatic cylinders can offer a better alternative to electrical or hydraulic actuators for certain types of applications and the pneumatic actuators

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provide the previously enumerated qualities at low cost. They are also suitable for clean environments and safer and easier to work with. However, position and force control of these actuators in applications that require high bandwidth is some how difficult, because of compressibility of air and highly nonlinear flow through pneumatic system components. A typical pneumatic system includes a force element (pneumatic cylinder), a command device (valve), connecting tubes, and piston, pressure and force sensors. The external load consists of the mass of external mechanical elements connected to the piston and perhaps a force produced by environmental interaction (Edmond and Yildirim, 2001). A schematic diagram of the pneumatic actuator system is shown in Figure 1.

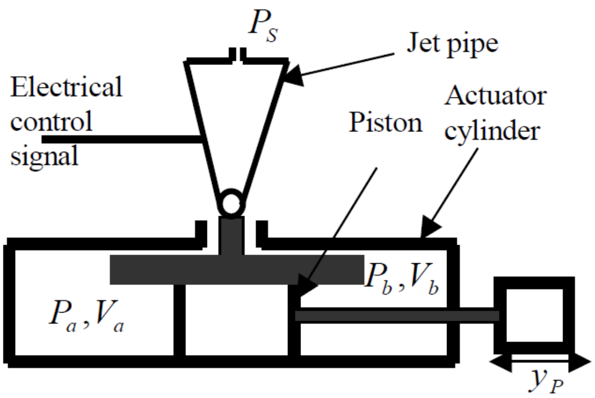


Fig. 1: Schematic diagram of pneumatic servo actuator system.

In this paper a method for tuning an H_∞ controller weights is presented. An optimal H_∞ controller will be obtained according to minimization of the required cost functions using particle swarm optimization (PSO), which is used to minimize the cost function as a powerful optimization method with high efficiency in comparison to other methods. This method tries to find the optimal values in a wide range of searching space through the interaction of particles in the population.

The PSO has become one of the most powerful methods for solving optimization problems. The method is proved to be robust in solving problems featuring nonlinearity and nondifferentiability, multiple optima, and high dimensionality. The advantages of the PSO are its relative simplicity and stable convergence characteristic with good computational efficiency (Majid *et al*, 2009).

2. Pneumatic Servo Actuator:

a. System Description:

The purpose of the servo actuator unit is to move the load by displacement (y_P) in compliance with command signals from the control section. Figure 1 shows the basic construction and operation of the electro-pneumatic servo actuator.

The source of power used in this type of actuator is compressed air supplied to the jet pipe. An electromagnetic force generated by the flowing electric current rotates the jet pipe. Reacting to the pressure differential in the cylinder cavities, the piston together with the rod moves with speed dependent on the airflow, air pressure and load. The diameter and stroke of the piston are 80mm and 50mm respectively. Output piston feedback is provided by a linear potentiometer, the slider of which is driven by the piston. The servo unit consists of a control surface actuator, a feedback transmitter, a polarized jet relay, and a power amplifier (Hazem *et al*, 2008). The minor loop of the servo shown in Figure 2 is used to ensure a proportional movement with respect to input commands.

b. System Mathematical Model and Dynamics:

The analysis of pneumatic actuators requires a combination of thermodynamics, fluid dynamics and the dynamics of motion. For constructing a mathematical model, three major considerations must be, involved (Hazem *et al*, 2009).

1. The mass flow rates through the valve.
2. The pressure, volume and temperature of the air, in cylinder.
3. The dynamics of the load.

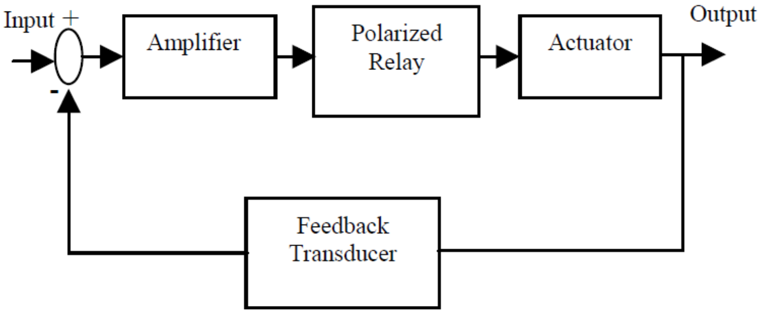


Fig. 2: Block diagram of servo actuator system.

The valve is a four port pneumatic jet pipe valve. This valve is treated as equivalent to two three-port valves, one of each side of the cylinder. Considering the left hand side of the cylinder, Figure 1, and the thermodynamic system is enclosed in the box, or control volume. Many studies have shown that for adequate models for controller design an isothermal behavior of the air may be assumed. Starting with the definition of the density, using the ideal gas equation and assuming an isothermal process the mass flow rates equations can be written as (Peter, 2007):

$$\dot{M}_a = \dot{\rho}_a V_a + \rho_a \dot{V}_a \tag{1}$$

$$-\dot{M}_b = \dot{\rho}_b V_b + \rho_b \dot{V}_b \tag{2}$$

Where $\dot{M}_a$ and $\dot{M}_b$ are the mass flow rates in (chambers (a) and ((b)) respectively, ρ is the density of the air, V_a and V_b are the volumes in chambers *a* and *b*.

For a symmetric cylinder the volumes in chambers *a* and *b* are given by:

$$V_a = V_o + A_{PYP} \tag{3}$$

$$V_b = V_o - A_{PYP} \tag{4}$$

where y_p is the position displacement, A_p is the piston area, V_o is the air volume in cylinder when the piston in mid point, V_a and V_b are the volumes in chambers *a* and *b*, respectively.

Differentiating equations (3) and (4) and substitute them in (1) and (2) the following equations will be obtained:

$$\dot{M}_a = \frac{1}{\alpha R T_a} \dot{P}_a (V_o + A_{yp}) + \frac{1}{\alpha R T_a} P_a A \dot{y}_P \tag{5}$$

$$\dot{M}_b = \frac{1}{\alpha R T_b} \dot{P}_b (V_o - A_{pyp}) + \frac{1}{\alpha R T_b} P_b A \dot{y}_P \tag{6}$$

where *R* is the gas constant, *D* is the specific heat ratio, T_a and T_b are the temperatures in chambers *a* and *b* respectively, P_a and P_b are the pressures in chambers *a* and *b* respectively.

Rearranging the equations (5) and (6) and adding the load dynamics equation that influences the overall performance of the piston motion, the system equations will be:

$$\dot{P}_a = \frac{\alpha R T_a}{(V_o + A_p y_p)} \dot{M}_a - \frac{\alpha P_a A_p}{(V_o + A_p y_p)} \dot{y}_P \tag{7}$$

$$\dot{P}_b = \frac{\alpha R T_a}{(V_o - A_{py\,p})} \dot{M}_b + \frac{\alpha P_b A_p}{(V_o + A_{py\,p})} \dot{y}_P \tag{8}$$

$$\ddot{y}_p = \frac{A_p}{M} P_a - \frac{A_p}{M} P_b - \frac{1}{M} F_L - \frac{1}{M} F_f \tag{9}$$

where M, F_L and F_f are the load mass, disturbing force and friction force respectively.

The equation that governs the mass flow rate of air through each control valve orifice is nonlinear equation and not suited for controller design. If a fast servo valve is used, the dynamics of the valve can be neglected. Assuming for the moment a positive input signal to the valve, a short line between valve and cylinder and chamber pressures of about half the supply pressure, the control valve equations will be simplified to be (Peter, 2007):

$$\dot{M}_a = K_V \frac{P_S}{2} u \tag{10}$$

$$\dot{M}_b = K_V \frac{P_S}{2} u \tag{11}$$

where K_V is the valve coefficient, P_S is the supply pressure and u is the electric valve input signal respectively.

Substituting equations (10) and (11) in equations (7) and (8) and combining the Laplace transformations of equations (7), (8) and (9) allows the operating point dependant transfer function model of the open loop system to be written as:

$$yP(s) = G(s)U(s) - G_d(s)F_d(s) \tag{12}$$

where

$$G(s) = \frac{2K \dfrac{\alpha R T A_p}{M V_o}}{s\left(s^2 + \dfrac{f}{M} s + \dfrac{2\alpha (A_p)^2 P_i}{M V_o}\right)} \tag{13}$$

and

$$G_d(s) = \frac{\dfrac{1}{M}}{s\left(s^2 + \dfrac{f}{M} s + \dfrac{2\alpha (A_p)^2 P_i}{M V_o}\right)} \tag{14}$$

where $K = K_V \frac{P_S}{2}$

This system considered, a four-port valve is used to control a double acting through rod cylinder. There are three nonlinearities in the pneumatic servo system. The first one is the nonlinear characteristic of the valve, and the other two nonlinearities are the volume and bulk modulus when they are used as coefficients in the equations. The nominal values of system parameters are given in Table 1 (Hazem *et al*, 2008).

Table 1: The nominal system model parameters.

System Parameter	Nominal Value
Piston area, A_P (m^2)	0.005
Air density, $\rho(\frac{Kg}{m^3})$	1.185
Ideal gas constant, R $(\frac{J}{Kg.K})$	287
Air volume when the piston in mid point, $V_o(m^3)$ $*10^{-4}$	2.5
Chamber pressure, P_i (bars)	3
Load mass M (Kg)	5
Viscous damping coefficient, f $(\frac{N.\sec}{m})$	60
Overall valve gain, $K(\frac{Kg}{s.V})$ $*10^{-3}$	3.4
Temperature of air source, T (K°)	293.15
Specific heat ratio, α	1.4
Potentiometer constant, $K_P(V/m)$	400

3. Uncertain Pneumatic Actuator System Model:

The pneumatic servo actuator system can be represented as shown in Figure 3. The parameters *a, b* and *c* can be defined as:

$$a = \frac{MV_i}{2K_p KA\alpha RT}, b = \frac{fV_i}{2K_p KA\alpha RT} \quad and \quad c = \frac{Ap_i}{K_p KRT} \tag{15}$$

The three physical parameters *a, b* and *c* are not known exactly therefore, they can be assumed that their values are within certain range. That is,

$$a = \bar{a}(1+\delta_a p_a),\ b = \bar{b}(1+\delta_b p_b),\ c = \bar{c}(1+\delta_c p_c) \tag{16}$$

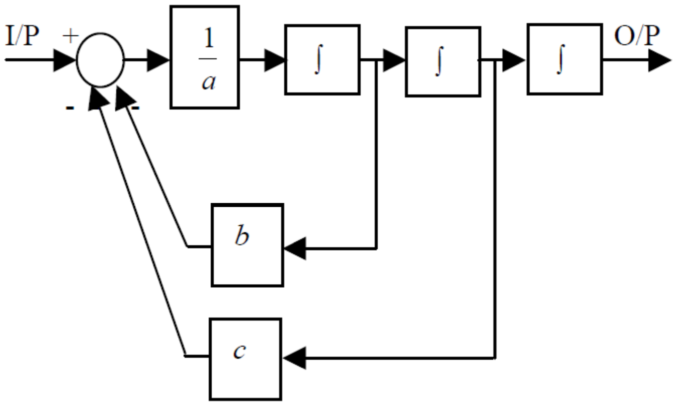


Fig. 3: Block diagram of pneumatic servo actuator system with its main parameters.

where $\bar{a}$ =0.1327×10^{-4}, $\bar{b}$ =0.1295×10^{-4}, $\bar{c}$ =0.01585 are the nominal values of *a, b and c*, p_a, p_b *and* p_c and δ_a, δ_b and δ_c represent the possible perturbations on these parameters. In this paper we let p_a =0.999246, p_b=0.64, p_c=0.174 and $-1\le \delta_a, \delta_b, \delta_c \le 1$. Not that this represent up to 99.9246% uncertainty in the parameter *a,* 64% uncertainty in the parameter *b* and 17.4% uncertainty in the parameter c.

The three constants blocks in Figure 3 can be replaced by block diagrams in terms of $\bar{a}$, p_a, δ_a , etc., in a unified approach. The quantity *1/a* can be represented as an upper linear transformation (LFT) in δ_a as:

$$\frac{1}{a}=\frac{1}{\bar{a}(1+p_a\delta_a)}=\frac{1}{\bar{a}}-\frac{P_a}{\bar{a}}\delta_a(1+p_a\delta_a)^{-1}=F_u(M_a,\delta_a)$$

with $$M_a=\begin{bmatrix}-p_a & \frac{1}{\bar{a}}\\ -p_a & \frac{1}{\bar{a}}\end{bmatrix} \qquad (17)$$

Similarly, the parameters $b=\bar{b}(1+p_b\delta_b)$, and $c=\bar{c}(1+p_c\delta_c)$ can be represented as an upper LFT in δ_b, and δ_c where $b=F_u(M_b,\delta_b)$ and $c=F_u(M_c,\delta_c)$

with $$M_b=\begin{bmatrix}0 & \bar{b}\\ p_b & \bar{b}\end{bmatrix}, and\ M_c=\begin{bmatrix}0 & \bar{c}\\ p_c & \bar{c}\end{bmatrix} \qquad (18)$$

Figure 4 shows the block diagram of the pneumatic system with uncertain parameters. The inputs and outputs of δ_a, δ_b and δ_c are denoted as y_a , y_b, y_c and u_a ,u_b , u_c respectively.

Let G_p denotes the input/output dynamics of the pneumatic system, which takes into account the uncertainty of parameters. G_p has four inputs (u_a, u_b, u_c, u), four outputs (y_a, y_b, y_c, y) and three states (x_1, x_2, x_3).

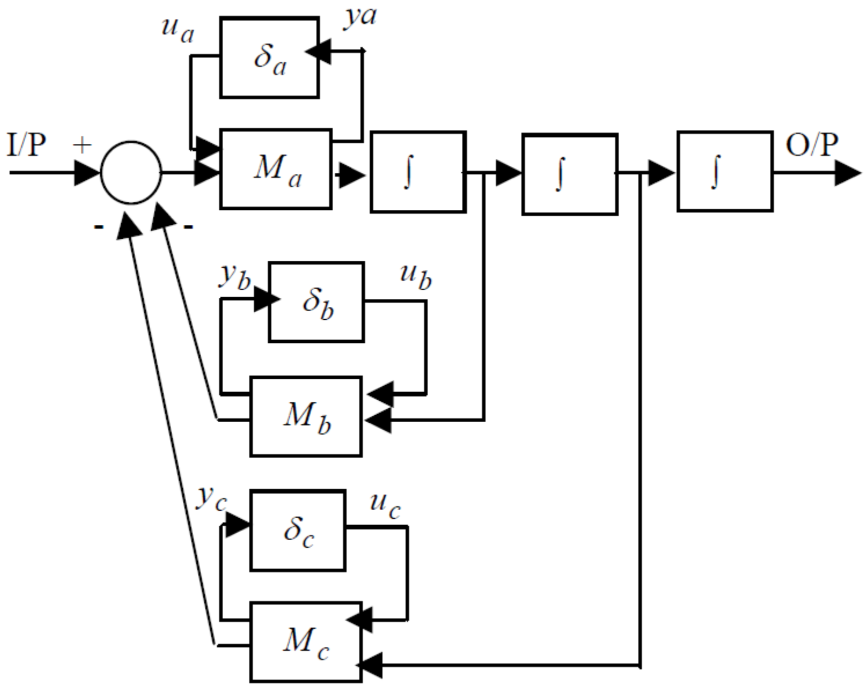


Fig. 4: Block diagram of the pneumatic system with uncertain parameters.

The state space representation of G_p is (Alok, 2007):

$$G_p = \begin{bmatrix} A & B1 & B2 \\ C1 & D11 & D12 \\ C2 & D21 & D22 \end{bmatrix} \tag{19}$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & \frac{-\bar{c}}{\bar{a}} & \frac{-\bar{b}}{\bar{a}} \end{bmatrix}, B1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -p_a & \frac{-p_a}{\bar{a}} & \frac{-p_c}{\bar{a}} \end{bmatrix}, B2 = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{\bar{a}} \end{bmatrix}, C1 = \begin{bmatrix} 0 & \frac{-\bar{c}}{\bar{a}} & \frac{-\bar{b}}{\bar{a}} \\ 0 & 0 & \bar{b} \\ 0 & \bar{c} & 0 \end{bmatrix}$$

$$D11 = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{\bar{a}} \end{bmatrix}, D12 = \begin{bmatrix} \frac{1}{\bar{a}} \\ 0 \\ 0 \end{bmatrix}, C2 = [1 \quad 0 \quad 0], D21 = [0 \quad 0 \quad 0], D22 = 0 \tag{20}$$

It is clear that the system matrix G_p has no any uncertain parameter and depends only on $\overline{abc}$, p_a , p_b, p_c and on the original system parameters.

The uncertain behavior of the original system can be described by an upper LFT representation $y = F_u(G_p,\Delta)u$ with diagonal uncertainty matrix Δ as shown in Figure 5. The open loop frequency response of the perturbed system is shown in Figure 6. These characteristics show that the bandwidth of the system decreases

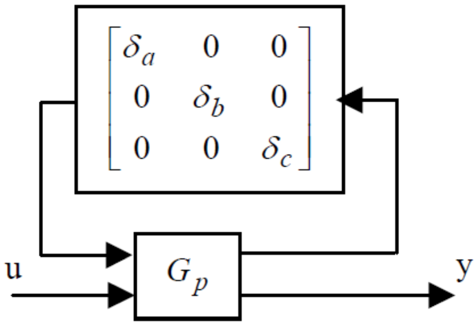


Fig. 5: Upper LFT representation of the system

with parameters variations until the system becomes slower. On the other hand, the phase margin also decreases that make the system tends to oscillate and be unstable in some cases.

4. Controller Design:
4.1 Bilinear transform and Weighting functions Selection:

Since the proposed system has *jw*-axis pole, the H_∞ controller, if it is reliably computed, would have marginally stable closed loop pole at the corresponding *jw*-axis location. This problem led to singularities in the equations that determine the state space realization of H_∞ control law. So a simple bilinear transform has been found to be extremely useful when used with robust control synthesis. This transformation can be formulated as a *jw*-axis pole shifting transformation (Richard and Michael, 1997):

$$s = \frac{\hat{s} + p_1}{\dfrac{\hat{s}}{p_2} + 1} \tag{21}$$

where $p_1 < 0$ and selected to be 0.1, p_2 is selected to be infinity. This is equivalent to simply shifting the *jw*-axis by p_1 units to the left. The H_∞ controller is obtained for the shifted system then it is shifted back to the right with the same units.

The design requirements and objectives for pneumatic servo actuator system in this paper is to find a linear, output feedback control $u(s)\ K_\infty\ (s)y(s)$ which ensures that the closed loop system will be internally stable. Also, the required closed loop system performance should be achieved for the nominal plant G_p.

The selection of weighting functions and weighting gains for specific design problem is not an easy procedure and often needs many iterations and fine-tuning and it is hard to find general formula for the weighting functions that will work in every case (Bittar and Sales, 1998). So to obtain a good control design, it is necessary to select suitable weighting functions. The performance and control weighting functions formulas used in this paper are (Richard and Michael, 1997; Zhou and Doyle, 1998):

$$W_p(s) = \frac{\beta(\alpha s^2 + 2\zeta_1 w_c \sqrt{\alpha} s + w_c^2)}{(\beta s^2 + 2\zeta_2 w_c \sqrt{\beta} s + w_c^2)} \tag{22}$$

$$W_u(S) = \left(\frac{s + \dfrac{w_{bc}}{\sqrt[k]{M_u}}}{\sqrt[k]{\varepsilon} s + w_{bc}} \right)^k \tag{23}$$

where β is the d.c. gain of the function which controls the disturbance rejection, α is the high frequency gain which controls the response peak overshoot, w_c is the function crossover frequency, ζ_1 and ζ_2 are the damping ratios of crossover frequency, w_{bc} is the controller bandwidth, *Mu* is the magnitude of $K_\infty S$, and ε is a small value. For the control weighting function in equation (23), the value of k was selected to be 2 for getting a second order function.

4.2 H_∞ *Controller Design:*

The H_∞ controller was designed so that H_∞ norm from input $W = F_d = dist$ to output $Z = \begin{bmatrix} e_p \\ e_u \end{bmatrix}$ is minimized. Where *dist* is the input disturbance signal, e_p , e_u are the weighted error and control signals. Figure 7 shows the standard feedback diagram of the system with weights. The generalized plant P is expressed by:

$$\begin{bmatrix} e_T \\ e_u \\ e \end{bmatrix} = \begin{bmatrix} W_p G_d & -W_p G_d \\ 0 & W_u \\ G_d & -G_p \end{bmatrix} \begin{bmatrix} dist \\ u \end{bmatrix} \tag{24}$$

where u is the control signal.

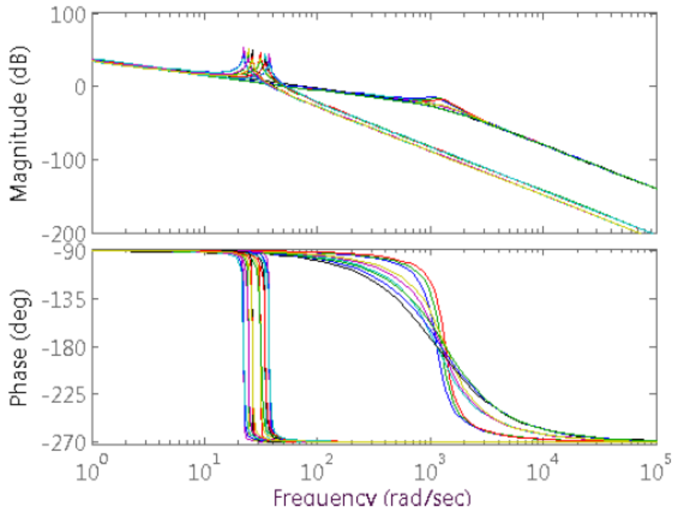


Fig. 6: Open loop frequency response characteristics with parameters uncertainty.

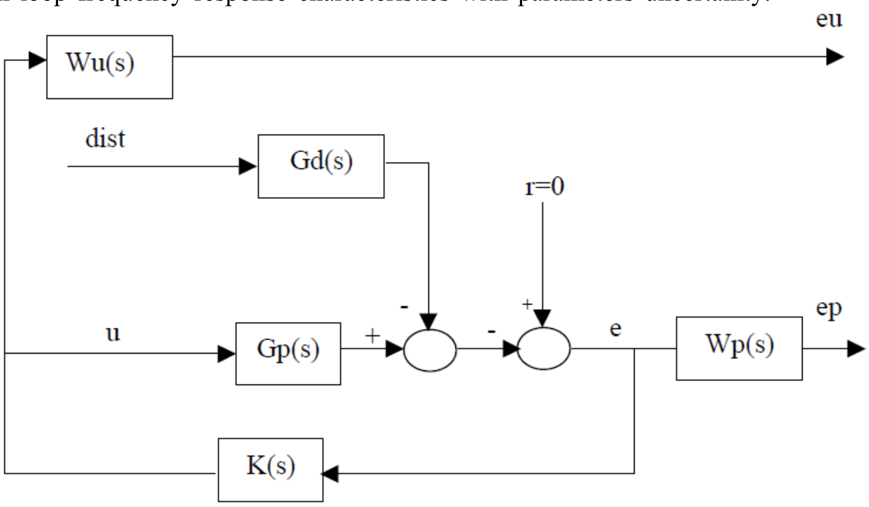


Fig. 7: The standard feedback diagram of the system with weights.

The lower linear fractional transformation of the generalized plant *P* and controller K_∞ can be described by:

$$F_1(P, K_\infty) = \begin{bmatrix} W_p G_d S \\ W_u G_d K_\infty S \end{bmatrix} \tag{25}$$

where $S = (1+G_pK_\infty)^{-1}$ is the sensitivity function of the nominal plant.

The objective of H_∞ control is to find the controller K_∞ that internally stabilizes the system such that $\|T_{zw}\|_\infty$ is minimized (Zhou and Doyle, 1998).

where $\|T_{zw}\|_\infty$ is the transfer function of the system from input *W* to output *Z* and can be expressed as:

$$\|T_{zw}\|_\infty = \left\| \begin{bmatrix} W_p G_d S \\ W_u G_d K_\infty S \end{bmatrix} \right\|_\infty \tag{26}$$

The H_∞ control minimizes the cost function in (26) using γ -iteration (Skogestad and Postlethwaite, 2005) to find the stabilizing controller such that $\|T_{zw}\|_\infty < \gamma$. So in this paper we have tried to find the optimal value of γ by using PSO algorithm for tuning the weighting functions that have a great effect on the overall design of H_∞ control technique. The optimal value of γ is the infimum overall γ such that the H_∞ control conditions stated in (Zhou and Doyle, 1998) are satisfied.

A suboptimal H_∞ controller was obtained using the following Matlab command:

$$>> [K_\infty, T_{zw}, \gamma_{suboptimal}] = h\inf syn(P, n_y, \gamma_{\max}, tol) \tag{27}$$

where n_y and n_u are the dimensions of *y* and *u*, $\gamma_{\min}$ and $\gamma_{\max}$ are the lower and upper bound for $\gamma_{optimal}$, and *tol* is the tolerance to the optimal value.

4.3 Tuning of Weights Using PSO:

The PSO algorithm is used to tune the selected weighting functions to obtain the optimal values of their parameters that ensure a controlled system with a good disturbance rejection, good transient response and low control signal. The fitness function used in PSO algorithm is the performance criteria stated in equation (26). The algorithm obtains the minimum value of the infinity norm of the performance criteria. The velocity and position equations of PSO algorithm are (Sheng-Fu *et al*, 2007):

$$v_i^{k+1} = w \times v_i^k + c_1 \times rand \times (x_i^b - x_i^k) + c_2 \times rand \times (x_i^g - x_i^k) \tag{28}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{29}$$

where v_i^k is the particle velocity, x_i^k is the current particle position, *w* is the inertia weight and it is selected to be 1.5, x_i^b and x_i^g are the best value and the global best value, *rand* is a random function, c_1 and c_2 are learning factors and are selected to be $c_1 = c_2 = 2$. The swarm size is (100) with (7-dimensions) (variables to be optimized) and the number of generations is (100). The proposed PSO algorithm for finding the optimal values of the weighting functions parameters is described by the flowchart shown in Figure 8. The overall block diagram of the system with PSO tuning algorithm is shown in Figure 9.

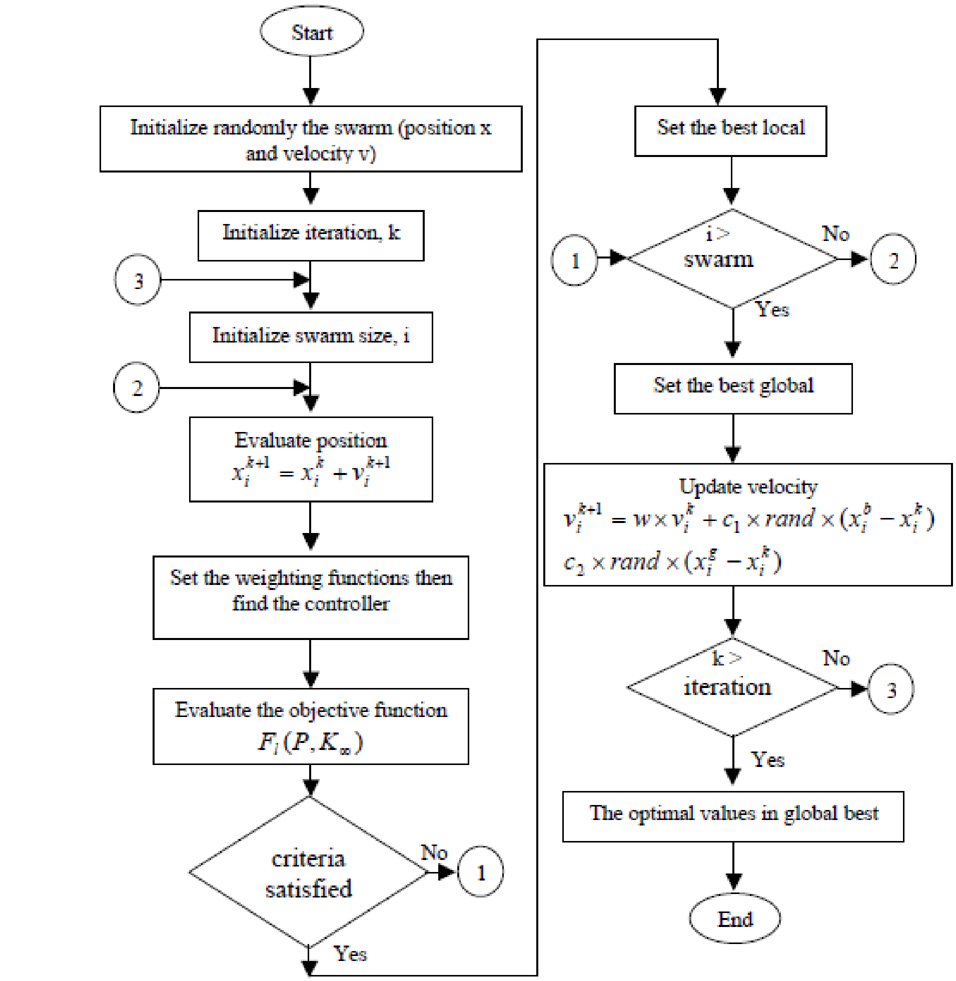


Fig. 8: Flowchart for tuning the weighting functions using PSO.

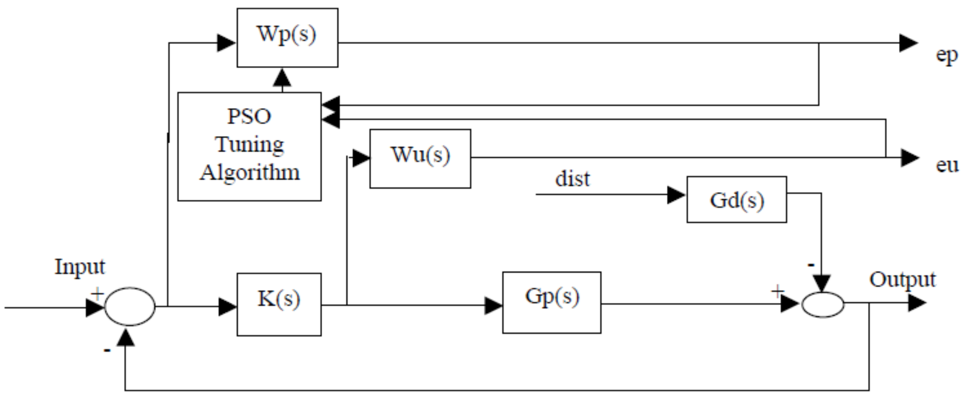


Fig. 9: Block diagram of the overall controlled system.

The interval for γ iteration is chosen between 0.1 and 10. The obtained controller is: -

$$K_{\infty} = \frac{2.021s^2 + 68.7s + 5840}{s^3 + 2373s^2 + 2.753\times10^4 s + 1.393\times10^5} \tag{30}$$

The optimal weighting functions parameters obtained using PSO algorithm are as follows: - β = 60.5724624, α = 0.01, w_c = 4.93, ζ_1 = 0.38, ζ_2 = 8.1242, M_u = 1.0011216, ε = 0.0 1 and w_{bc} = 1.7 with γ = 0. 8559.

6. Simulation Results:

Figure 10 shows the singular values of closed loop system with the controller K_∞. It is seen that the maximum value of the closed loop system is less than one, that's mean that the condition $\left\|W_p(1+G_pK_\infty)^{-1}\right\|_\infty < 1$ is satisfied. Figure 11 shows the frequency characteristics of the sensitivity function compared with the inverse of the performance weighting function. It is clear that the sensitivity function lies below the inverse of W_p that is means that the performance criterion was satisfied. Figure 12 shows the frequency response of the open loop perturbed system with the controller. It is clear that the system is always stable with all parameters uncertainty that is robust stability was satisfied. Figure 13*a* and *b* show the time response characteristics of the closed loop nominal system and perturbed system. The time response characteristic of the system subjected to disturbance is shown in Figure 14. For a practical requirements, it is required the control signal to be small to avoid the problem of the saturation.

Figure 15 shows the frequency characteristics of the control signal where a small maximum value was obtained.

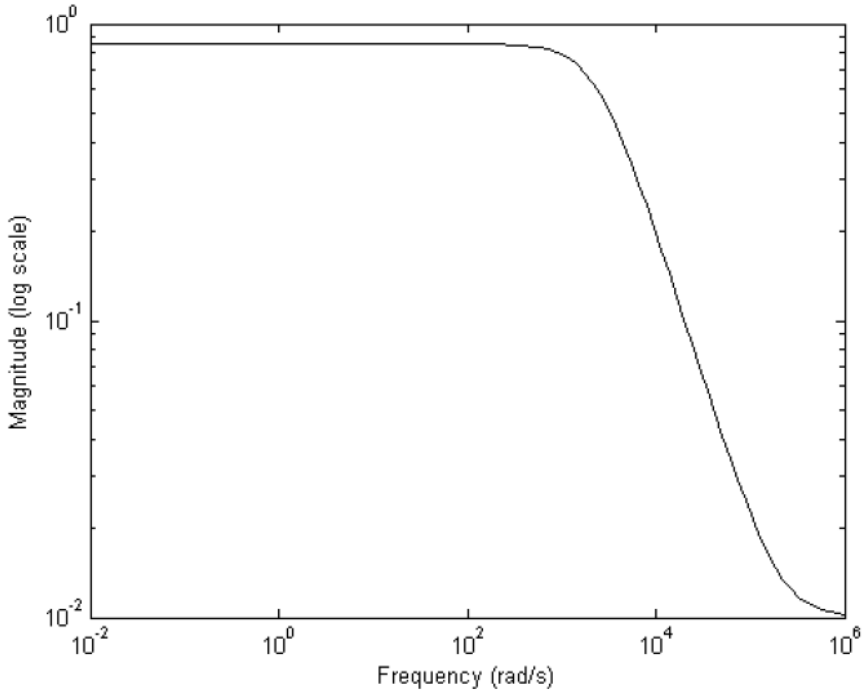


Fig. 10: The largest singular Value of the closed loop controlled system T_{ZW} .

Conclusion:

A robust H_∞ controller has been designed to assure robust stability and robust performance of a pneumatic servo actuator system with parametric uncertainty. The particle swarm optimization method (PSO) was used for tuning the weighting functions. The optimal parameters of the weighting functions that are obtained using PSO algorithm led to obtain a robust controller that achieves the position control of pneumatic actuator. It was also shown that the proposed method for tuning the weighting functions is easy to implement and better results could be obtained using this method. Finally a simple and low order robust controller was obtained.

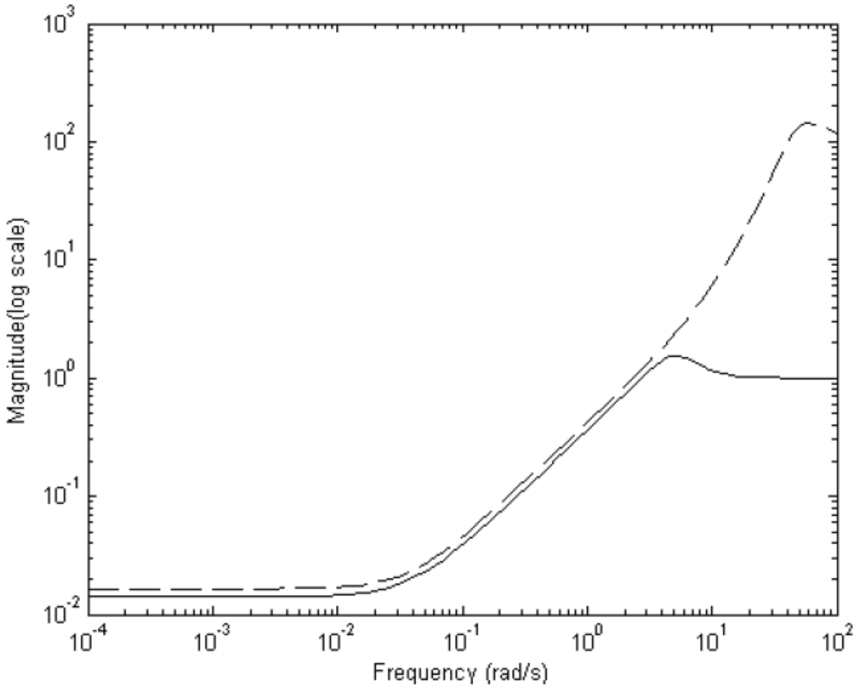


Fig. 11: Frequency characteristics of sensitivity function S (solid line) and the inverse of the weighting function Wp (dashed line).

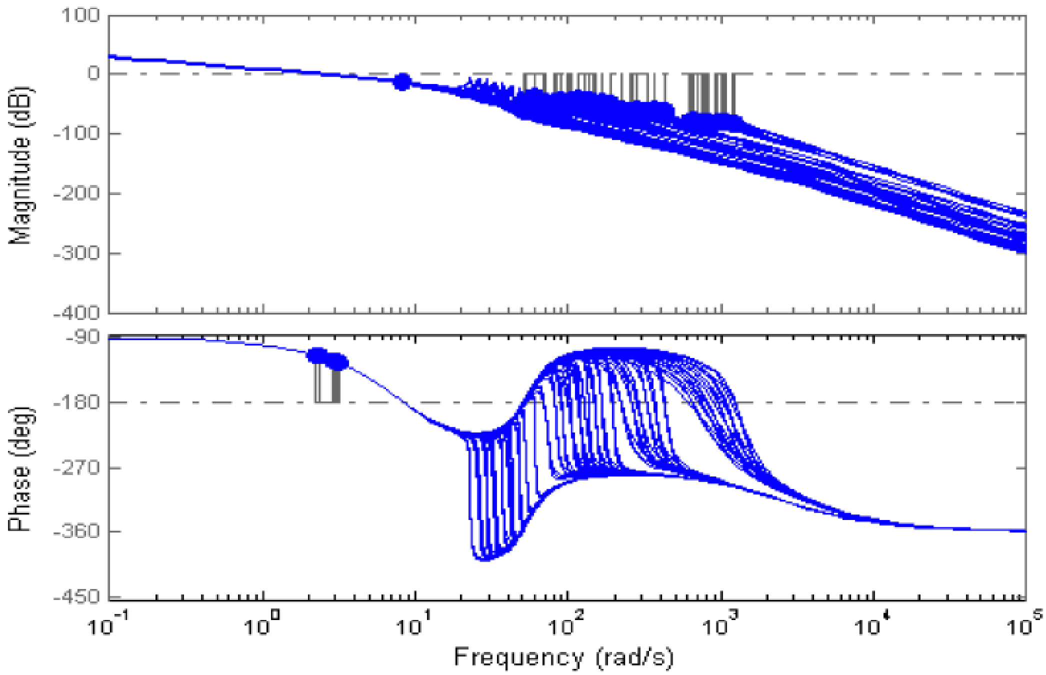
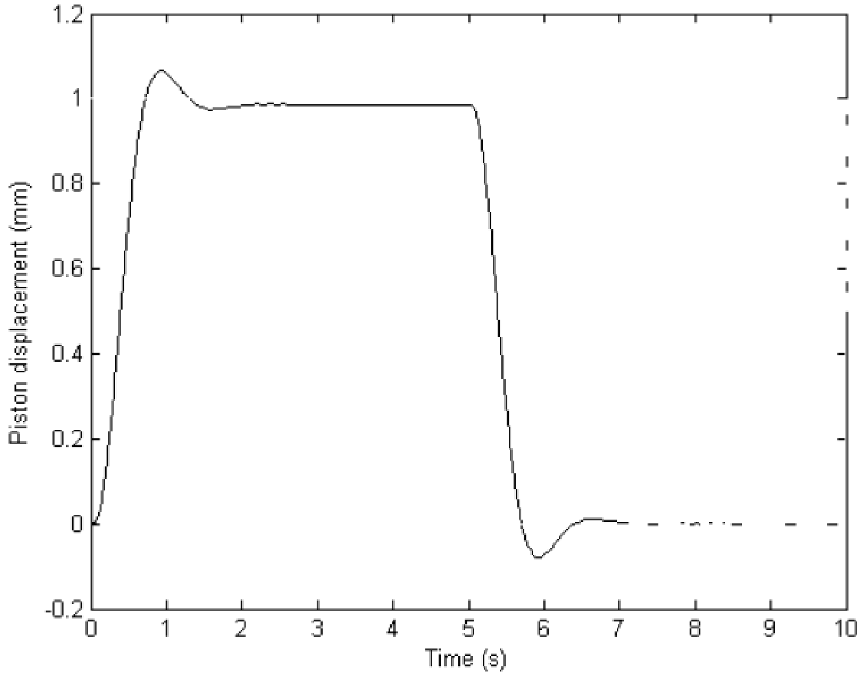
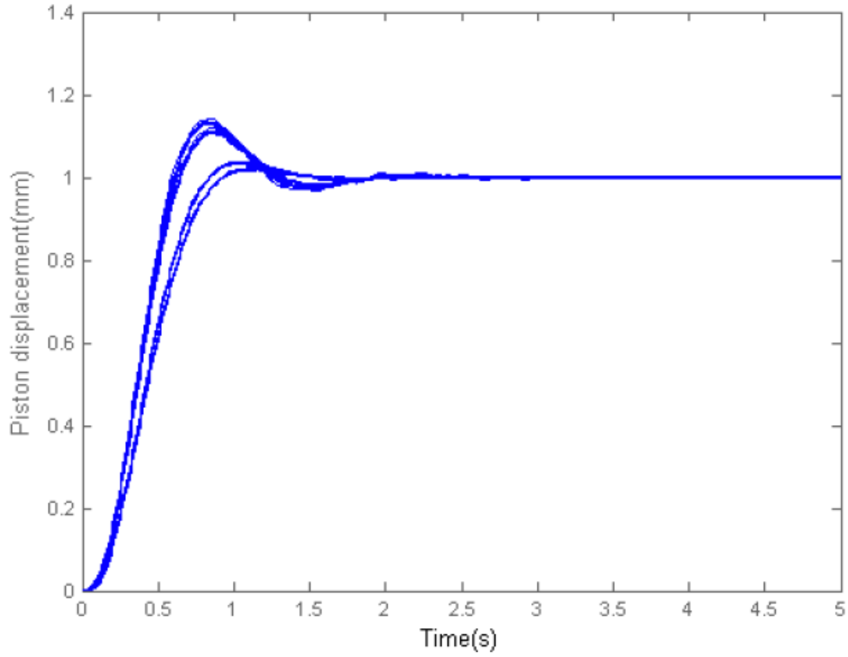


Fig. 12: Frequency response characteristics of perturbed controlled system.



(A)



(B)

Fig. 13: Closed loop time response characteristics of the closed loop controlled system a) nominal system b) perturbed system.

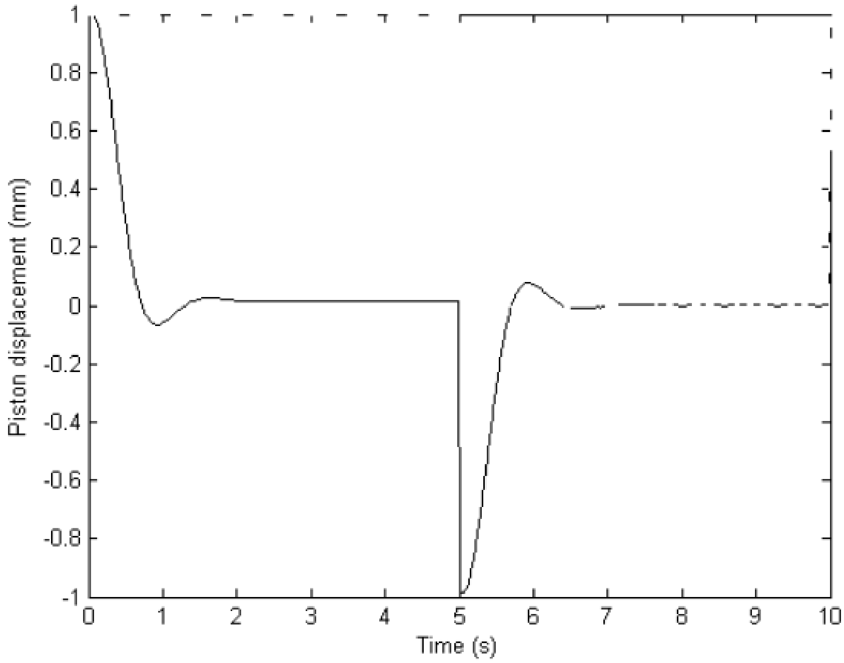


Fig. 14: Time response characteristics of the closed Loop controlled system subjected to disturbance.

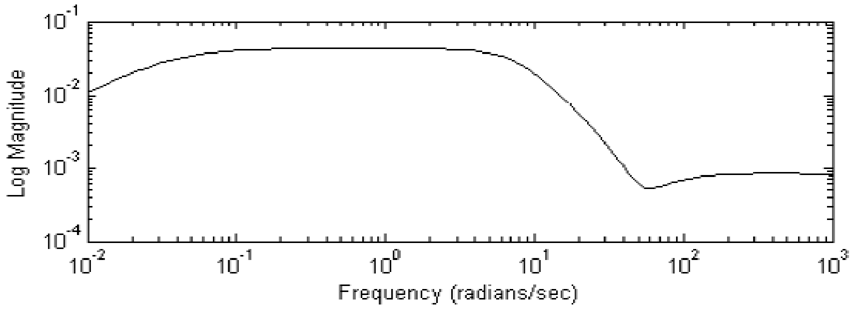


Fig. 15: Frequency response characteristics of the control signal.

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